REPORT NO. GDSS-SP-87-018

(NASA-CR-179318) TURNAROUND OPERATIONS ANALYSIS FOR OTV. VOLUME 3: TECHNOLOGY DEVELOPMENT PLAN Final Report (General Dynamics Corp.) 118 p CSCL 22B G3/16

N88-20342

Unclas 0133338

TURNAROUND OPERATIONS ANALYSIS FOR OTV

FINAL REPORT
VOLUME III
TECHNOLOGY DEVELOPMENT PLAN

February 1988

GENERAL DYNAMICS
Space Systems Division

GDSS-SP-87-018

Turnaround Operations Analysis for OTV

Final Report

Vol. III Technology Development Plan

February 1988

The cost estimates contained herein represent technical and programmatic definition developed to date and may change as further technical information becomes available. These estimates are for planning purposes only and do not constitute a commitment on the part of General Dynamics.

Prepared for

NASA-Marshall Space Flight Center
Huntsville, Alabama

Prepared by

Advanced Space Programs
General Dynamics Space System Division
Huntsville, Alabama

08650

FORWORD

This study report was prepared by General Dynamics Space Systems (GDSS) Division for the National Aeronautics and Space Administration/Marshall Space Flight Center (NASA/MSFC) in accordance with contract NAS8-36924, Data Requirement Number DR-4. The results were developed from August 1986 to January 1988.

This volume describes an integrated technology development plan for the technologies required to process both GBOTVs and SBOTVs. The plan includes definition of the tests and experiments to be accomplished on the ground, in a Space Shuttle Sortie Mission, on an Expendable Launch Vehicle or at the Space Station as a Technology Development Mission (TDM). The plan reflects and accommodates current and projected research and technology programs where appropriate.

The GDSS personnel responsible for the work are listed as follows:

Bill Ketchum:	Study Manager
John Maloney:	Deputy Study Manager/Space Accommodations
Luis Pena:	Operational Requirements, Functional Analysis, Trade Studies
John Washburn:	Shuttle/Centaur Data Base, Ground Operations
Johna Hanson:	Turnaround Operations Analysis
Paul Rizzo:	OTV and Space Station Design Interface Requirements
Sandy Witt:	Turnaround Operations, Support Equipment Costs
Mark Liggett:	Cryogenic Propellant Management

For further information contact:

Bill Ketchum
OTV Study Manager
General Dynamics
Space Systems Division
600 Boulevard South, Suite 201
Huntsville, AL 35802
205-88-0660

Don Saxton
OTV Study Manager
NASA/Marshall Space
Flight Center
PF 20
Huntsville, AL 35812
205-544-5035

PRECEDING PAGE BLANK NOT FILMED

TABLE OF CONTENTS

SUMMARY

1.0 INTRODUCTION
- 1.1 Objective
- 1.2 Groundrules and Guidelines
- 1.3 OTV Missions
- 1.4 Study Approach
- 1.5 OTV Configurations

2.0 INTEGRATED TECHNOLOGY DEVELOPMENT PLAN

3.0 AUTOMATED FAULT DETECTION/ISOLATION AND SYSTEM CHECKOUT SUMMARY

4.0 CRYOGENIC PROPELLANT TRANSFER, STORAGE, AND RELIQUEFACTION
- 4.1 Propellant Transfer Technology Analysis & Ground Testing
- 4.2 Propellant Storage Technology Analysis & Ground Testing
- 4.3 Propellant Reliquefaction Technology Analysis & Ground Testing
- 4.4 Orbital Testing Options
  - 4.4.1 Option 1
  - 4.4.2 Option 2
  - 4.4.3 Option 3
  - 4.4.4 Recommendation

5.0 OTV MAINTENANCE/SERVICING/SUPPORT EQUIPMENT
- 5.1 OTV Maintenance and Servicing Technology Analysis and Ground Testing
- 5.2 OTV Maintenance and Servicing Technology Shuttle Sortie Mission
- 5.3 OTV Maintenance and Servicing Technology Space Station Technology Development Mission

6.0 DOCKING AND BERTHING
- 6.1 Docking and Berthing Analysis and Ground Testing
- 6.2 Docking and Berthing Shuttle Sortie Mission
- 6.3 Docking and Berthing TDM

7.0 OTV/PAYLOAD MATING/INTERFACE
- 7.1 OTV/Payload Mating/Interface Development Tests Requirements
- 7.2 OTV/Payload Mating/Interface Shuttle Sortie Mission
- 7.3 OTV/Payload Mating/Interface TDM

8.0 TECHNOLOGY DEVELOPMENT TESTS COST ANALYSIS
- 8.1 Automated Fault Detection/Isolation and System Checkout
- 8.2 Cryogenic Propellant Transfer, Storage and Reliquefaction
- 8.3 OTV Maintenance/Servicing/Support Equipment
- 8.4 Docking and Berthing
- 8.5 OTV/Payload Mating/Interface
- 8.6 Integrated Technology Development Plan Funding

SUMMARY

The Turnaround Operations Analysis for Orbital Transfer Vehicles (OTV) Study was conducted by General Dynamics Space Systems Division (GDSS), Contract No. NASA8-36924, under the direction of the National Aeronautics and Space Administration (NASA)/Marshall Space Flight Center (MSFC).

The basic study was for 12 months with an add-on which brought the total time to 18 months. The results of the total study are presented in this final report.

The objectives and accomplishments during this study were to adapt and apply the newly created database of Shuttle/Centaur ground operations. Previously defined turnaround operations analyses were to be updated for ground-based OTVs (GBOTVs) and space-based OTVs (SBOTVs), design requirements identified for both OTV and Space Station accommodations hardware, turnaround operations costs estimated, and a technology development plan generated to develop the required capabilities.

The study provided technical and programmatic data for NASA pertinent to OTV ground and space operations requirements, turnaround operations, task descriptions, timelines and manpower requirements, OTV modular design and booster and Space Station interface requirements, OTV Space Station accommodations design and operations requirements, SBOTV accommodations development schedule, cost and turnaround operations requirements, and a technology development plan for ground and space operations and space-based accommodations facilities and support equipment. Significant conclusions of the effort were:

a. Shuttle/Centaur Lessons Learned

1. Semi-automated cryo stage can be extended to full automation
2. Identified manual operations: candidates for automation
3. Airborne support equipment (ASE) for ground-based cargo bay OTV will be complex (dump and dual fault tolerant)
4. Dedicated facility recommended
5. Facility should provide capability to simulate launch vehicle interfaces and Space Station interfaces
6. Reduce number of moves

b. Ground Processing Operations for GBOTVs

1. Ground processing of ground-based cargo bay OTVs nearly identical to Shuttle/Centaur

2. Ground processing of ground-based unmanned cargo vehicle (UCV) OTVs similar to Atlas/Centaur and Shuttle/Centaur

3. Ground processing of space-based OTV relatively simple
   (a) Simple ASE
   (b) No orbiter cryo integration
   (c) No payload integration

4. Recommend integrated processing facility for GBOTVs: Two shift operations

5. Automated ground processing operations where possible

6. GBOTV initial launch 6 weeks (9200 manhours)

7. Nominal turnaround GBOTV 5 weeks + mission (7800 manhours)

8. UCV OTV initial launch 5 weeks (6500 manhours)

9. UCV OTV nominal turnaround 5 weeks + mission (6200 manhours)

10. Recommend shared ground processing facility for SBOTV

c. Ground Processing Operations SBOTV

1. Ground processing of space-based OTV relatively simple
   (a) Simple ASE
   (b) No orbiter cryo integration
   (c) No payload integration

2. Recommend shared ground processing facility for SBOTV

3. SBOTV single shift operations - Initial Launch 11 weeks (10,332 manhours)

d. Space Processing Operations SBOTV

1. SBOTV can be based at Space Station and turned around in safe and cost-effective manner

2. Use teleoperations for SBOTV turnaround tasks except for aerobrake thermal protection system: extravehicular activity (EVA)

3. Nominal turnaround for SBOTV:
   (a) 63 manhours in space
   (b) 763 manhours on ground
   (c) 7 days + mission

4. SBOTV turnaround propellant resupply, support equipment maintenance, and long-term cryogenic facility maintenance = 1273 manhours per year average at the Space Station (3 men maximum per task)

e. OTV Design and Interfaces

1. Need proposed modular design of SBOTV to meet projected turnaround times

2. Interfaces between OTV launch vehicle and accommodations have been identified

f. Space Station Design, Support, and Interface Requirements

1. SBOTV accommodations/support equipment and interfaces with the Space Station have been identified

2. Minimum scars required on initial Space Station for SBOTV accommodations

g. Support Equipment Development Cost and Schedule

1. Development of OTV accommodations technology requires
   (a) Analyses, tests, and simulations on the ground
   (b) A cryogenic experiment on an expendable launch vehicle (ELV) in space, and Shuttle sortie missions for maintenance/servicing experiment
   (c) A maintenance/servicing Technology Development Mission (TDM) and possibly a cryogenic TDM at the Space Station

2. $1.4 billion development cost for OTV accommodations/support equipment for SBOTV initial operating capability (IOC) in 2001

h. Turnaround Operations Costs. Average $34M per year for on-orbit tasks to turnaround a SBOTV

i. Technology Development Plan. The following is the priority listing of the technologies needed to be developed for a SBOTV:

1. Propellant transfer, long-term storage, and reliquefaction
2. Automated fault detection/isolation and checkout system
3. Docking and berthing
4. Maintenance/servicing operations and facilities/support equipment
5. Payload mating/interface

j. Propellant Transfer, Long-Term Storage, and Reliquefaction Technology Development Requirements

1. Analyses, simulation and ground testing

2. An orbital experiment launched on an ELV with a H_2 tank scale factor between 0.1 and 0.4

3. Depending on the scale factor on the ELV experiment which produces different confidence levels of extrapolation to full scale, these options are seen to be able to reach operational capability
   (a) 0.4-scale ELV (Titan IV) can lead to direct development of operational system
   (b) 0.1-scale ELV (Atlas/Centaur) would require additional full-scale ground testing, or
   (c) Full scale H_2 tank testing at the Space Station

4. Too early to recommend which approach should be pursued

k. Automated Facility Detection/Isolation and Checkout System. Development of GBOTV and SBOTV operation technology requires analyses, simulation, and ground testing of automated fault detection/isolation and checkout system.

l. Maintenance/Servicing Operations and Facilities/Support Equipment. Development of SBOTV accommodations technology requires analyses, simulation, ground testing, and Shuttle sortie missions, and a Space Station TDM for docking and berthing, maintenance/servicing, operations/support equipment, and payload mating/interface.

SECTION 1

INTRODUCTION

The Orbital Transfer Vehicle (OTV) Concept Definition and System Analysis Studies, and earlier Space Station Architecture Studies, have shown that space-based OTVs (SBOTVs) offer potential economic benefits over ground-based OTVs (GBOTVs). In addition, the Definition of Technology Development Missions for Early Space Station -- OTV Servicing Study, completed in 1984 and the present OTV Concept Definition Studies have generated preliminary operational scenarios and requirements for SBOTVs.

The General Dynamics Space Systems Division (GDSS) OTV Servicing Study used our Eastern Test Range (ETR) Atlas/Centaur processing as a data base. This has provided a sound background for a preliminary projection of activities to maintain and service an upper stage in space. Recently, the design, launch processing, and manufacture of the Shuttle/Centaur was essentially completed. The launch processing was performed up to taking the stage out to the launch pad before the program was cancelled. The Centaur, redesigned for increased performance and Shuttle integration requirements, is closer to an OTV than the vehicle used on Atlas.

Now that the Shuttle/Centaur integrated test planning data and launch processing has been completed, GDSS has used this information as the data base for the conduct of this follow-on study. Processing information has been updated with this new data. In addition, with this new data, it was possible to provide more detailed information on the most desirable methods for turning around an SBOTV at the Space Station, the support personnel and equipment needed, and the operations costs. The Shuttle/Centaur data base -- that of a cryogenic upper stage launched from the Shuttle -- has provided National Aeronautics and Space Administration (NASA) a comprehensive, substantiated turnaround approach for Space Station/OTV planning.

The Space Transportation Architecture Studies (STAS) currently being performed for NASA and Department of Defense (DoD) have placed strong emphasis on the reduction of operations costs through simplification, automation, etc. This turnaround operations analysis study provides additional information to support the pursuit of this cause in the upper-stage area.

1.1 OBJECTIVES

The basic objectives of this study are to adapt and apply the newly created data base of Shuttle/Centaur ground operations planning to update previously defined turnaround operations analyses for GBOTVs and SBOTVs, identify design requirements for both OTV and Space Station accommodations hardware, and estimate turnaround operations costs. Specific objectives which support these basic objectives are as follows:

a. Define OTV turnaround operations requirements, concepts, and scenarios.

b. Conduct operations functional and task analyses.

c. Assess the impact of OTV turnaround operations on ground facilities and Space Station design and support requirements.

d. Identify OTV design requirements of effective turnaround operations.

e. Analyze turnaround operations costs and identify operations costs drivers.

f. Generate Technology Development Plan.

1.2 GROUND RULES AND GUIDELINES

The following ground rules and guidelines were used in the performance of this study:

a. Make maximum use of prior and current projects.

b. Space Shuttle will be the Earth launch vehicle: $100M [Eastern Launch Site (ELS)].

c. Revision 8 nominal mission model.

d. Space Station Initial Operational Capability (IOC) 1994.

e. Orbital Maneuvarable Vehicle (OMV) will be available.

f. Orbiter Cargo Bay (OCB), Aft Cargo Carrier (ACC), and Unmanned Cargo Vehicle (UCV) Launched GBOTVs

g Reference SBOTV configuration: Defined by Marshall Space Flight Center (MSFC) for Space Station Phase B.

h. SBOTV life is 40 missions.

i. Definition of a Task: Any activity or collection of activities serving a specified purpose relative to turnaround of the OTV.

j. Definition of a Resource: Any quantity required for the performance of a task: Each resource will be defined to appropriate depth for concept definition.

k. Functional tasks will be completely defined.

l. Tasks sequencing information will be provided.

m. Functional/task data base compatible with government computers.

1.3 OTV MISSIONS

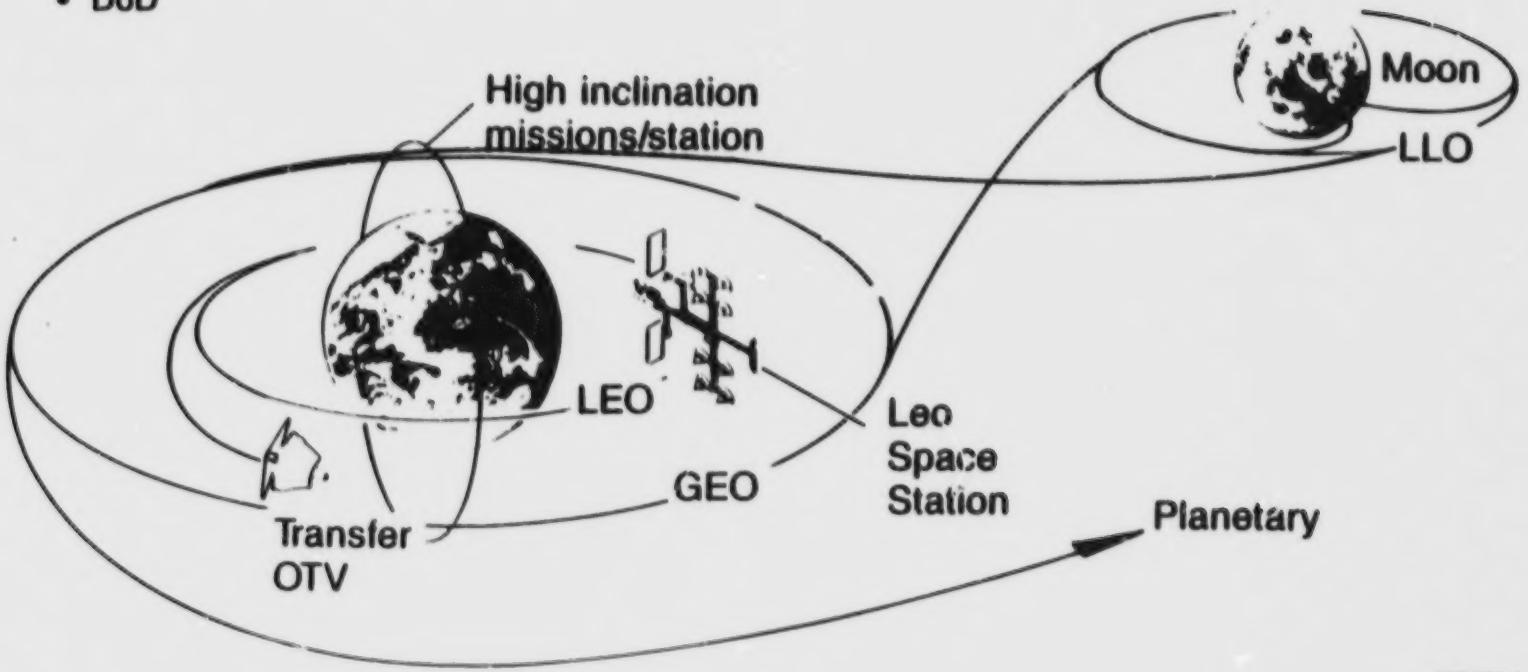
The OTV will accomplish a wide range of missions, from Earth orbital to lunar and planetary, both unmanned and manned. (See Figure 1-1.) Routine transfer of civilian and military payloads between low Earth and geosynchronous orbit are planned, including delivery, retrieval, and in-place servicing. The operational scenario and mission profile of the OTV include: initial delivery of the OTV with subsequent delivery of payloads and propellants from the Earth to the OTV/servicing facility by either the Space Transportation System (STS) of unmanned launched vehicles; integration of payloads on the OTV and refueling of the OTV from propellant storage tanks on the servicing facility; departure of the OTV and payloads to high orbits, translunar, or interplanetary trajectories; then return of the OTV via aerobraking to the servicing facility.

Earth orbital

- Multiple GEO payload delivery
- Large GEO satellite delivery
- GEO satellite retrieval
- Experimental GEO platform
- GEO shack elements
- Manned GEO sortie
- GEO shack logistics
- DoD

Beyond earth

- Unmanned planetary
- Unmanned lunar orbit
- Unmanned lunar surface
- Lunar orbit station
- Manned lunar sorties/logistics



272.353-1
14116212-21C

Figure 1-1. OTV Missions

For purposes of this study, NASA has specified that the NASA/MSFC Revision 8 nominal mission model be used. Figure 1-2 indicates the number of missions to be performed each year for Revision 8 and when the major mission drivers first occur.

1.4 STUDY APPROACH

The overall approach to this study will be a step-wise translation of Shuttle/Centaur launch processing experience to: 1) an expendable GBOTV, 2) a reusable GBOTV, and 3) a reusable SBOTV. (See Figure 1-3.) Each step will be separately defined to allow a clear delineation of the functions and requirements which are peculiar to each vehicle/basing mode. The major differences between each step are called out to the right of the blocks.

This approach provides more insight for extrapolation from Shuttle/Centaur launch processing to a reusable SBOTV.

Figure 1-4 presents the study schedule, delineating the tasks to be performed and the program reviews. The technical work was accomplished in 16 months with the reporting completed in 18 months.

To accomplish the study objectives, OTV turnaround operations requirements, concepts, and scenarios were defined; operations functional and task analyses were conducted; the impact of OTV turnaround operations on Space Station design and support requirements was assessed; OTV design requirements for effective turnaround operations were identified; turnaround operations costs were analyzed; and operations cost drivers were identified. In addition, a technology development plan was generated to develop the capability to process both GBOTVs and SBOTVs.

1.4.1 TASK 1 - GROUND AND SPACE OPERATIONS REQUIREMENTS. The Shuttle/Centaur ground processing data base was used to assess and identify requirements for OTV processing. As we evaluated the data base, we determined which operational functions were Centaur peculiar and which ones were required for OTV processing. The data consisted of operations plans which established the processing and critical paths for Shuttle/Centaur at the ELS. The plan had about 155 tasks defined and listed about 90 procedures to be accomplished during Centaur processing, before it was transported to the vertical processing facility. The operations plans for the vertical processing facility and Complex 39 were also assessed. This was the type of data that we used to determine if all processes had been identified in the current OTV space-based operations. We then updated the OTV data previously defined to include the requirements identified here.

The Shuttle/Centaur data base also included manpower loading for each task and equipment requirements.

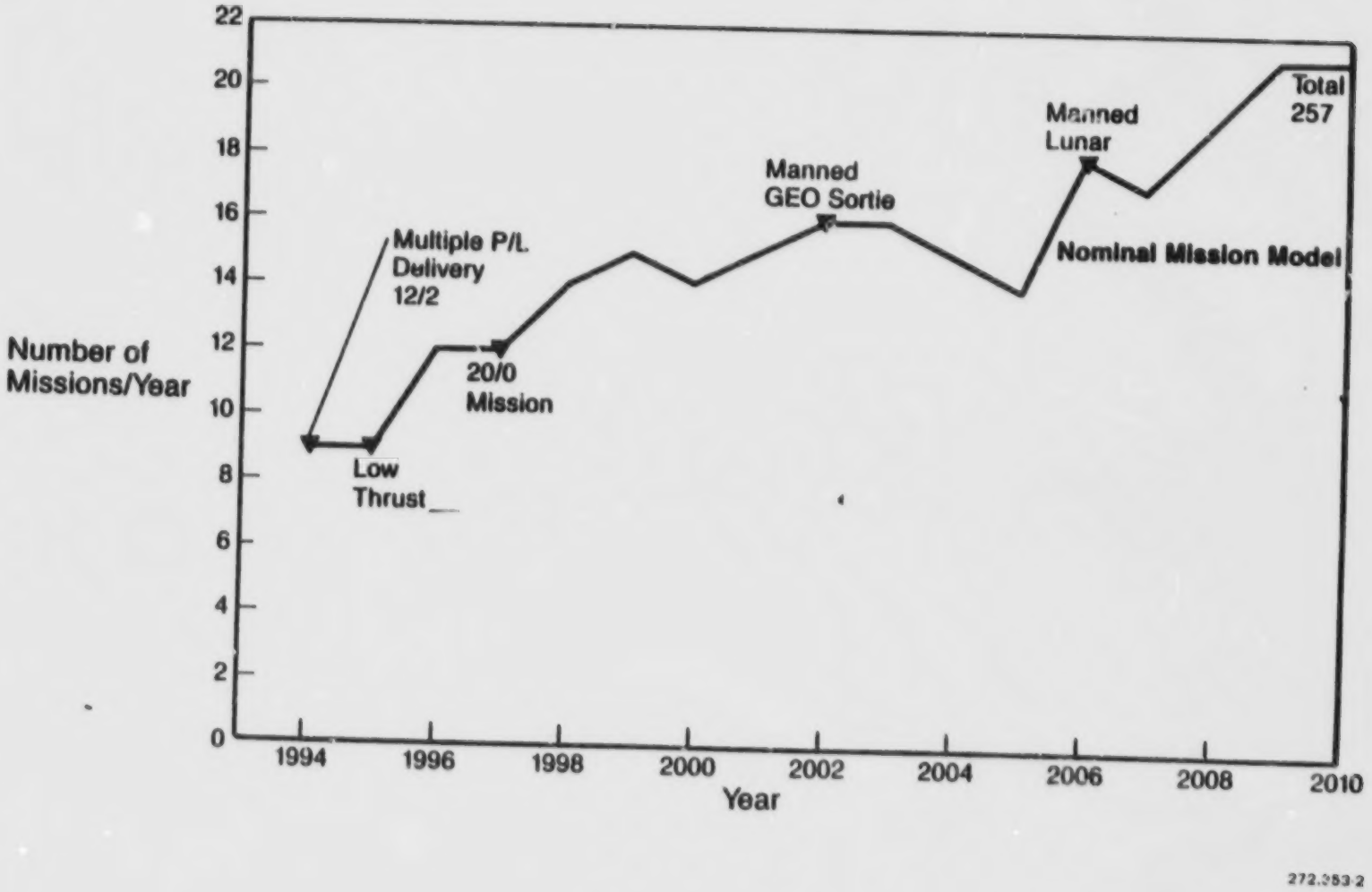


Figure 1-2. Revision 8 Mission Model

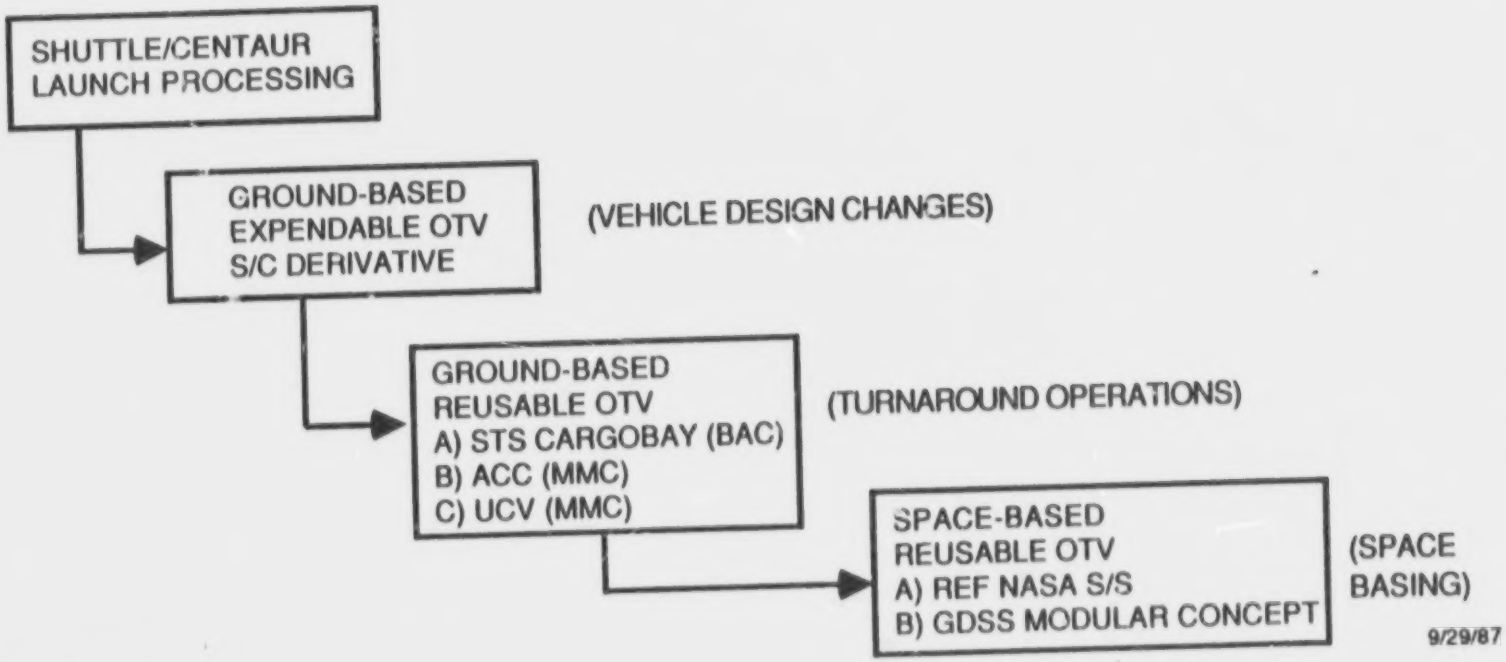


Figure 1-3. Approach

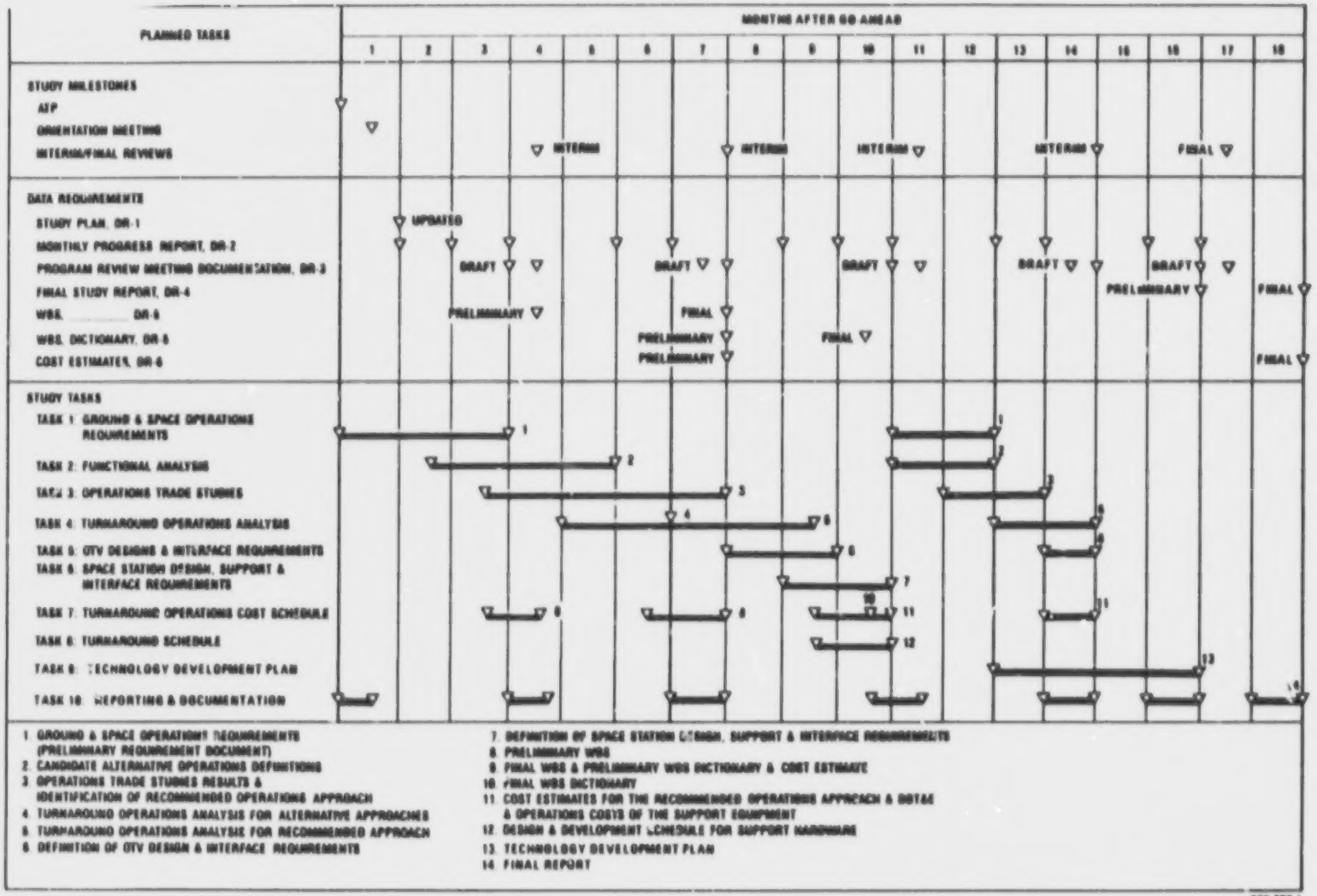

PLANNED TASKS
MONTHS AFTER GO AHEAD
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
STUDY MILESTONES
ATP
ORIENTATION MEETING
INTERIM/FINAL REVIEWS
INTERIM
INTERIM
INTERIM
INTERIM
FINAL
DATA REQUIREMENTS
STUDY PLAN, DR-1
UPDATED
MONTHLY PROGRESS REPORT, DR-2
PROGRAM REVIEW MEETING DOCUMENTATION, DR-3
DRAFT
DRAFT
DRAFT
DRAFT
DRAFT
FINAL STUDY REPORT, DR-4
PRELIMINARY
FINAL
WBS, _____ DR-5
PRELIMINARY
FINAL
WBS DICTIONARY, DR-5
PRELIMINARY
FINAL
COST ESTIMATES, DR-6
PRELIMINARY
FINAL
STUDY TASKS
TASK 1: GROUND & SPACE OPERATIONS REQUIREMENTS
TASK 2: FUNCTIONAL ANALYSIS
TASK 3: OPERATIONS TRADE STUDIES
TASK 4: TURNAROUND OPERATIONS ANALYSIS
TASK 5: OTV DESIGNS & INTERFACE REQUIREMENTS
TASK 6: SPACE STATION DESIGN, SUPPORT & INTERFACE REQUIREMENTS
TASK 7: TURNAROUND OPERATIONS COST SCHEDULE
TASK 8: TURNAROUND SCHEDULE
TASK 9: TECHNOLOGY DEVELOPMENT PLAN
TASK 10: REPORTING & DOCUMENTATION
1 GROUND & SPACE OPERATIONS REQUIREMENTS (PRELIMINARY REQUIREMENT DOCUMENT)
2 CANDIDATE ALTERNATIVE OPERATIONS DEFINITIONS
3 OPERATIONS TRADE STUDIES RESULTS & IDENTIFICATION OF RECOMMENDED OPERATIONS APPROACH
4 TURNAROUND OPERATIONS ANALYSIS FOR ALTERNATIVE APPROACHES
5 TURNAROUND OPERATIONS ANALYSIS FOR RECOMMENDED APPROACH
6 DEFINITION OF OTV DESIGN & INTERFACE REQUIREMENTS
7 DEFINITION OF SPACE STATION DESIGN, SUPPORT & INTERFACE REQUIREMENTS
8 PRELIMINARY WBS
9 FINAL WBS & PRELIMINARY WBS DICTIONARY & COST ESTIMATE
10 FINAL WBS DICTIONARY
11 COST ESTIMATES FOR THE RECOMMENDED OPERATIONS APPROACH & DDT&E & OPERATIONS COSTS OF THE SUPPORT EQUIPMENT
12 DESIGN & DEVELOPMENT SCHEDULE FOR SUPPORT HARDWARE
13 TECHNOLOGY DEVELOPMENT PLAN
14 FINAL REPORT

Figure 1-4. Study Schedule

1.4.2 TASK 2 - FUNCTIONAL ANALYSIS. The requirements identified in Task 1 were integrated with other requirements such as guidelines and ground rules, Space Station configuration baseline, the SBOTV concept defined by NASA/MSFC to arrive at probable scenarios for processing. We looked at these requirements and determined whether they were essential for maintaining and operating an OTV. Any potential tall poles were identified, and all functional requirements were documented. The functional analys s includes the operations necessary to assemble a SBOTV on-orbit, space-based turnaround operations, servicing/maintenance, payload integration, launch and retrieval operations. We assessed these functions and incorporated any new requirements that were essential and appropriate and deleted or modified those that were not appropriate.

We formulated alternative scenarios from the functional requirements and defined operational methods for accomplishing each alternative scenario. These methods incorporated alternative means to accomplish each task, such as different types of facilities and automation for ground processing and different kinds of crew involvement, extravehicular activity (EVA) or intravehicular activity (IVA), and mechanized alternatives such as teleoperations, automatic disconnects on the vehicle, robotics, or a combination for SBOTV. These alternatives and the designated GBOTV concepts were compared in a trade study analysis to select a recommended approach in Task 3.

1.4.3 TASK 3 - OPERATIONS TRADE STUDIES. In this task we compared the attributes of each alternative operation identified in Task 2 to select a recommended approach. We defined the selection criteria used to evaluate the alternative operations. These criteria included design, operational, and cost factors that have an impact on the selection of a recommended approach. This task relied on inputs from Tasks 4 and 7 to provide adequate supporting data for evaluation of the approaches. The alternatives and selection criteria were then presented in a trade comparison matrix. The recommended operations approach was selected using the data from this matrix.

1.4.4 TASK 4 - TURNAROUND OPERATIONS ANALYSIS. This task generated the timeline analyses for both ground and space processing based on the requirements and alternative operational definitions derived in Tasks 1 and 2. These analyses provided the OTV turnaround operations data necessary to support the trade studies and to develop to more detail the trade study recommended operations by defining the ground-based and space-based resources.

We updated the existing OTV timelines to meet new requirements and created new timelines for new alternative functions. The timelines include OTV turnaround operations on the ground and in space and the maintenance of any identified Space Station OTV accommodations, such as orbital support equipment. Our timelines were created from data that was developed on task analysis worksheets. The task analysis worksheets are on computer disc and are used to document the pertinent detailed tasks, task durations, and resulting manhours. We also provided data to an appropriate level on task description sheets. The task description sheet has the task identification code, task descriptor, purpose, task description, task duration and frequency, and the resource requirements.

1.4.5 TASK 5 - OTV DESIGN AND INTERFACE REQUIREMENTS. Using the results and recommendations of the turnaround operations analysis and the definition of the baseline GEOTV and SBOTV, we identified and defined OTV design and interface requirements for basing on the ground and at the Space Station. These covered the areas of accessibility, modularity, size, and weight of Orbital Replacement Units (ORUs); ORU attachment and removal provisions; controlled storage; self-test to the ORU or subsystem level; handling and mating provisions; payload mating provisions; accommodations for mechanical, fluid, and electrical disconnects; zero-g propellant transfer; and management system, etc.

1.4.6 TASK 6 - SPACE STATION DESIGN, SUPPORT AND INTERFACE REQUIREMENTS. Using the definition of the space-based support equipment, the operational maintenance, checkout and launch requirements, the definition of an SBOTV to meet the operational and interface requirements, and the baseline Space Station functional and design concept, we performed a design requirements analysis to determine the accommodation needs from the Space Station to support the SBOTV. This entailed identifying the operational and physical Space Station support and interface requirements to accommodate the retrieval, maintenance, servicing, checkout, payload mating, and launching of the OTV. These included the mechanical, fluid and electrical interfaces; cg considerations; spares storage; pressurized volume; propellant transfer, and storage system; docking, berthing, and handling equipment; environmental protection; and crew support requirements.

1.4.7 TASK 7 - TURNAROUND OPERATIONS COST ESTIMATES. A WBS and WBS dictionary was developed which was used in the performance of the trade studies. The task's costs of the recommended operational approach considering the manpower resources required were estimated. The operational costs were divided into two categories: fixed and variable costs. Fixed costs are associated with a base cost not dependent on the number (within limits) of OTVs processed during a period of time (normally 1 year). Operation cost drivers were also identified. The design development test and evaluation (DDT&E) and operations costs of the support equipment for the recommended operational approach were also identified.

1.4.8 TASK 8 - TURNAROUND SCHEDULE. We developed a master program development schedule for the OTV and the evolution of the Space Station from IOC to the growth station which can support an SBOTV. From this, we generated a design and development schedule for the turnaround operations support hardware. The schedule included the technology development activities including analysis and ground testing, Shuttle sortie flights and Technology Development Missions (TDMs) required at the Space Station to develop the turnaround operations capability.

1.4.9 TASK 9 - TECHNOLOGY DEVELOPMENT PLAN. We generated an integrated technology development plan for the technologies required for ground and space processing OTVs. This was a single plan which defined the tests and experiments to be performed on the ground, on expendable flight experiments, on Space Shuttle sortie missions, and on the early Space Station. The ground processing technologies included: 1) fault detection/isolation and system checkout, 2) visual inspection, 3) leak check and detection, 4) documentation, and 5) facility checkout and operations provisions.

The space processing technologies included: 1) propellant transfer, storage, and reliquefaction, 2) OTV docking and berthing, 3) EVA operations, 4) OTV/payload mating, 5) maintenance facilities/support equipment, and 6) automated fault detection/isolation and system checkout. The plan included task objectives, requirements, mode of accomplishment, schedules, resources, operations, and expected products. The plan reflected and accommodated current and projected research and technology programs where appropriate.

1.5 OTV CONFIGURATION

Configurations evaluated for functional differences (See Figure 1-5) include Atlas/Centaur; Shuttle/Centaur; Shuttle/Centaur derivative expendable OTV; Boeing Ballute OCB launched reusable GBOTV: Martin ACC launched reusable GBOTV; and SBOTV (MSFC reference configuration). In addition the Martin UCV OTV (see Figure 1-6) was evaluated. The configurations will be shown in more detail in the following sections.

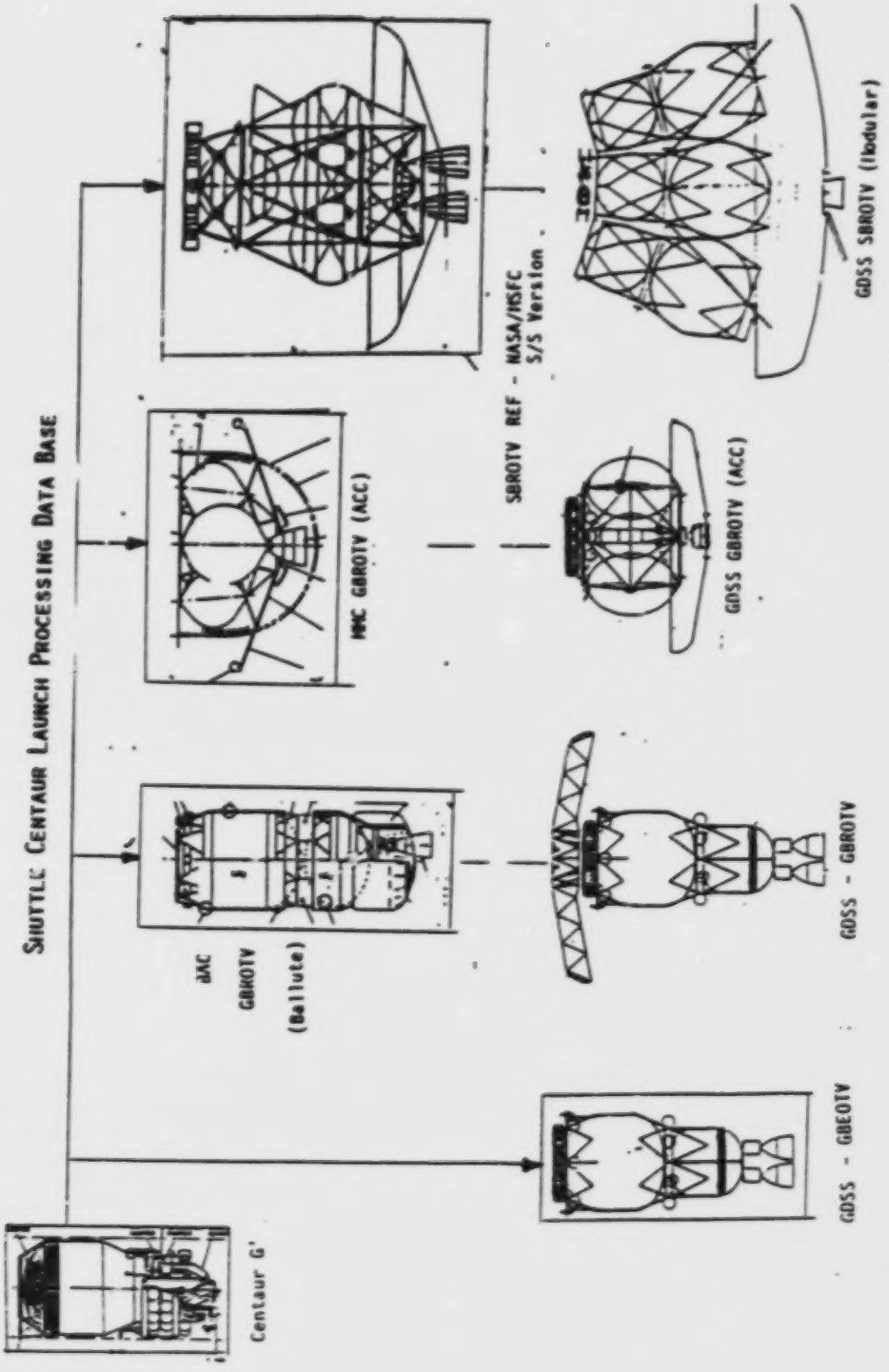


Figure 1-5. OTV Configurations

ORIGINAL PAGE IS
OF POOR QUALITY

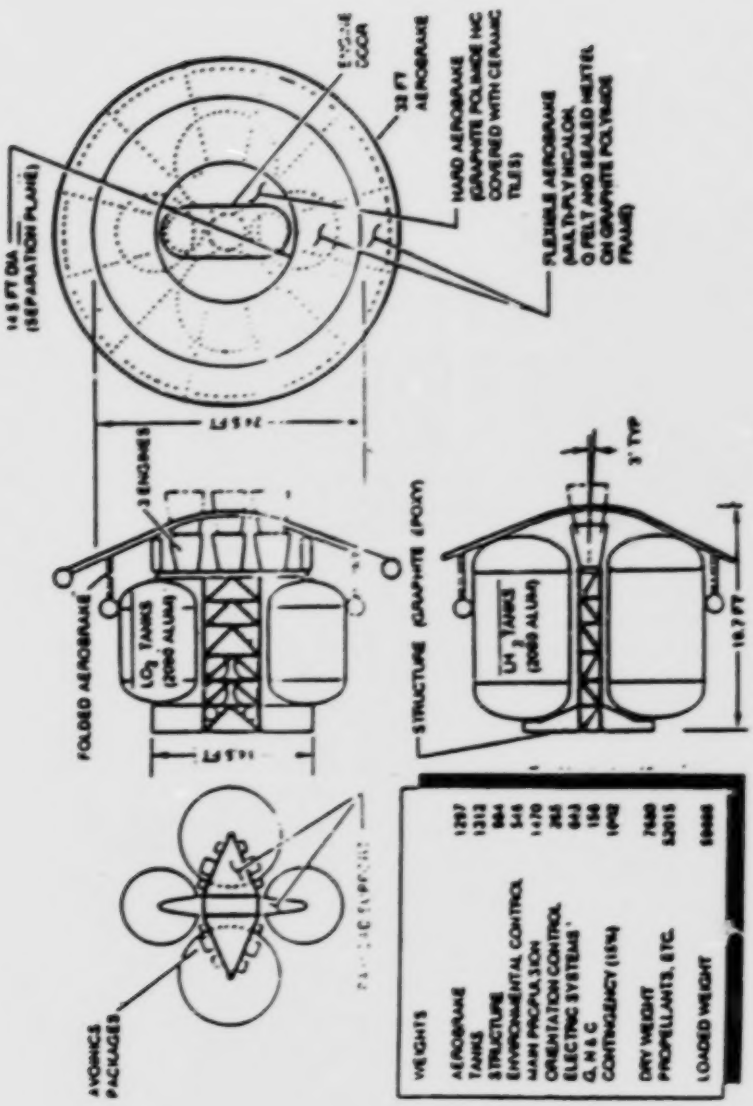


Figure 1-6. Unmanned Cargo Vehicle (UCV) OTV - Martin

ORIGINAL PAGE IS
OF POOR QUALITY

SECTION 2
INTEGRATED TECHNOLOGY DEVELOPMENT PLAN

This section identifies the requirements for analyses, ground tests, Shuttle Sortie or ELV tests, and Space Station Technology Development Missions (TDM) to be performed on the Space Station to develop the capability to maintain and service an OTV on orbit. This work is an update of the plan to generate on the OTV Servicing Study Phase II NAS8-35039 (Report No. GDC-SP-83-067) done for MSFC.

Figure 2-1 show the overall design and development schedule for the OTV accommodations/support equipment from Phase A thru several launches to the Space Station and when the expected IOC will occur. The development schedules for the Space Station, GBOTV and SBOTV are also shown to see how the main elements of the program are related and integrated. The Space Station's first launch is scheduled to occur in 1994, man tended operations will start in 1995, and the Phase I IOC will occur in 1996. The Phase II build-up will be completed in 1999 which allows the SBOTV accommodations to build-up to begin.

The expected development of the GBOTV is shown from the present Phase A studies to an IOC in 1997 and how this development might augment the SBOTV. In addition, the expected development of the SBOTV is shown from the pre-phase A studies which are going on at the present time to the IOC in 2001. It turns out that this schedule directly parallels the development schedule of the SBOTV accommodations/support hardware. Also on the chart is shown the technology development schedule for the accommodations/support hardware. This includes ground, Shuttle/ELV, and Space Station activities. The technology schedule is expanded on the following charts.

The technology requirements for ground processing of ground based OTV's as well as the ground processing of space-based OTV's are shown in Figure 2-2. These requirements have been identified from the OTV Concept Definition Studies and OTV Turnaround Operations Studies that have taken place in the last five years.

Figure 2-3 show the development schedule for the ground operations technology. The areas of technology development are called out on the chart.

Applications analysis will take place starting in 1989 and the selection of applications for testing would take place in 1991. Testing would continue through 1993 up to the start of the GBOTV Phase C/D and through 1995 up to the start of the SBOTV and accommodations phase C/D.

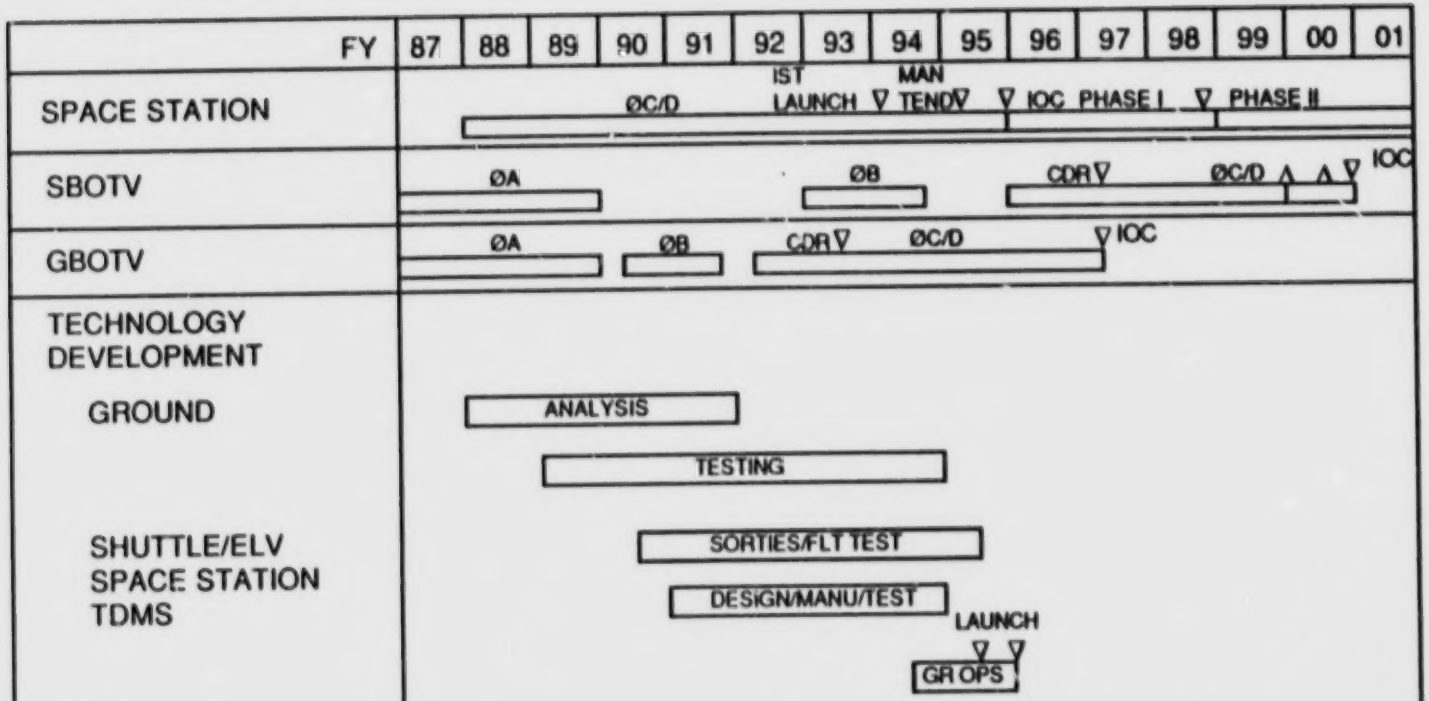
The technology requirements for space basing on OTV are shown in Figure 2-4. They have been identified previously in an MSFC-funded study referenced on the chart. We reevaluated these requirements in this study and found they haven't changed. An updated technology development plan for these technologies was developed as part of this study.

Figure 2-5 shows the development schedule for one of the areas of space operations technology, namely cryogenic fluid transfer, long term storage, and fluid management.

An experiment launched on an ELV has been proposed for an orbital experiment. The launch is scheduled for early in 1994 and the experiment is designed to have an operating life on orbit of two years. This data will be available by the CDR for the Phase C/D of the OTV accommodations program. Depending on the size of the orbital experiment and the expected results especially pertaining to the confidence level of the scaling factors, three options for the next phase are envisioned. (1) If the orbital experiment provides enough confidence in the scaling factors, then no additional technology testing is required and the propellant depot can be developed according to the schedule on Figure 2-1, (2) If the orbital experiment doesn't provide enough confidence in the scaling factors, then a large scale gorund test would have to be performed before starting the propellant depot C/D, or (3) If the orbital experiment doesn't provide the required confidence nor would the large scale ground test, then a technology development mission (TDM) at the Space Station would have to be performed before CDR of the accomodations C/D.

FIGURE 2-1

DESIGN AND DEVELOPMENT SCHEDULE FOR OTV'S AND OTV ACCOMMODATIONS/SUPPORT HARDWARE



11/24
JV/M

FIGURE 2-2

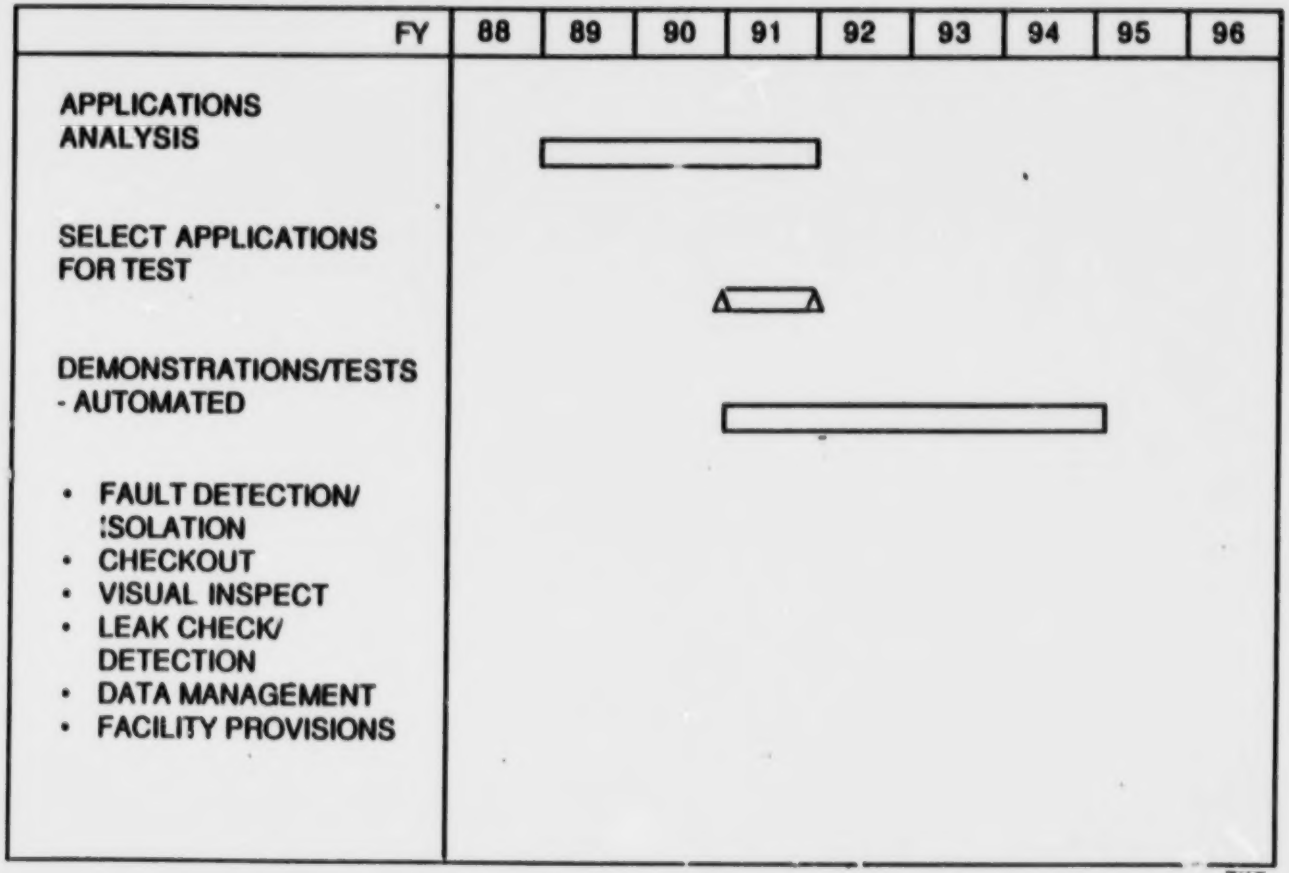
TECHNOLOGY REQUIREMENTS
- GROUND PROCESSING (FOR GB & SB OTV)

AUTOMATED FAULT DETECTION/ISOLATION AND SYSTEM CHECKOUT INCLUDING

- VISUAL INSPECTION
- LEAK CHECK AND DETECTION
- DATA MANAGEMENT
- FACILITY CHECKOUT AND OPERATIONS PROVISIONS

FIGURE 2-3

OTV ACCOMMODATIONS/SUPPORT HARDWARE TECHNOLOGY DEVELOPMENT - GROUND OPERATIONS



7/15

FIGURE 2-4

TECHNOLOGY REQUIREMENTS
*SPACE-BASED OTV SERVICING/MAINTENANCE

1. CRYOGENIC PROPELLANT TRANSFER, STORAGE AND RELIQUEFACTION

2. AUTOMATED FAULT DETECTION/ISOLATION AND SYSTEM CHECKOUT

3. OTV DOCKING AND BERTHING

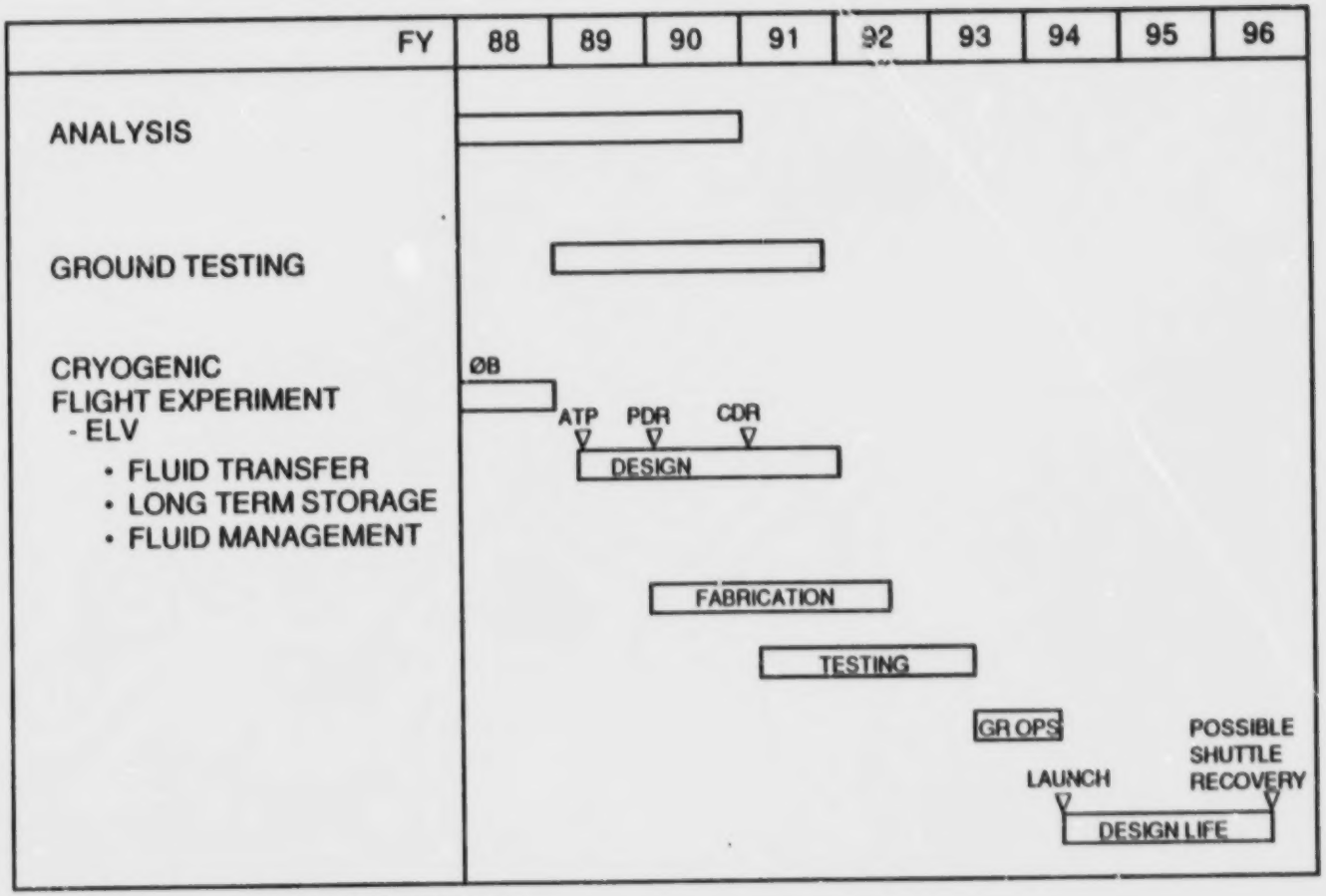
4. OTV MAINTENANCE/SERVICING OPERATIONS AND FACILITIES/SUPPORT EQUIPMENT
   - TELEOPERATORS/ROBOTICS
   - CREWMEN TRANSLATION EQUIPMENT
   - OTV TRANSLATING & BERTHING ROTATION EQUIPMENT
   - CONTROLS AND DISPLAYS
   - EVA OPERATIONS

5. OTV/PAYLOAD MATING/INTERFACE

*TECHNOLOGY DEVELOPMENT MISSIONS FOR EARLY SPACE STATION ORBIT TRANSFER VEHICLE SERVICING PHASE II.

FIGURE 2-5

OTV ACCOMMODATIONS/SUPPORT HARDWARE *TECHNOLOGY DEVELOPMENT - CRYOGENIC PROPELLANT ELV EXPERIMENT



*MAY REQUIRE SPACE STATION TDM

11/24/87

It is too early to recommend the best option but it appears that the third option with a large enough orbital experiment on the Space Station be flown so that there will be good confidence in the scaling factors that will be used to extrapolate to the full scale data would be a good approach. The pros and cons of the three options are discussed in Section 4.0.

Figure 2-6 shows the development schedule for the other area of space operations technology, namely on-orbit servicing and maintenance which also includes docking/berthing and payload mating. Servicing and maintenance involves both the SBOTV and the OTV accommodations themselves.

The technology development plans include ground testing/simulations, shuttle sorties, and a technology demonstration mission (TDM) on the Space Station. Proposed Shuttle sortie missions would evaluate the various elements of servicing and maintenance shown on the chart in zero-g. These sortie flights would be accomplished before the CDR for the Space Station TDM.

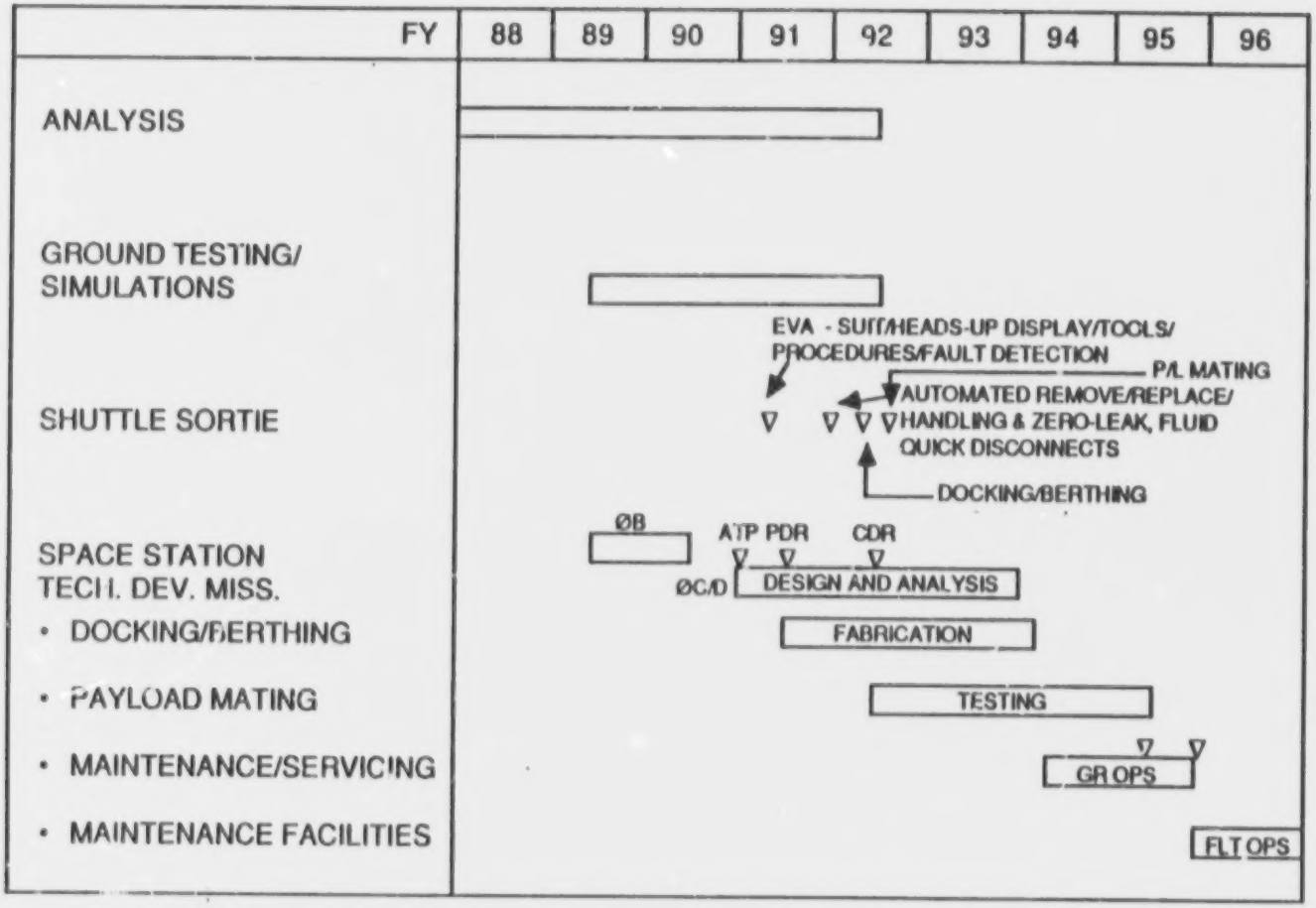
The Space Station TDM would be launched in 1995 and be ready for the flight operations in 1996 at IOC of the station. The data collected would provide verification of the design and approach during the Phase C/D of the SBOTV and OTV accommodations.

Figure 2-7 lists the type of data which was generated for the plan for the technologies identified on the previous charts. This data is presented in the following sections.

GENERAL DYNAMICS
Space Systems Division

FIGURE 2-6

OTV ACCOMMODATIONS/SUPPORT HARDWARE TECHNOLOGY DEVELOPMENT - MAINTENANCE/ SERVICING OPERATIONS AND SUPPORT EQUIPMENT



11/24/87

GENERAL DYNAMICS
Space Systems Division

FIGURE 2-7

TASK 9 TECHNOLOGY DEVELOPMENT PLAN - STUDY TASKS

DEFINE REQUIRED:

- ANALYSES
- GROUND TESTS
- SHUTTLE SORTIE AND/OR ELV TESTS
- SPACE STATION TECHNOLOGY DEMONSTRATION MISSIONS (TDMS)

IDENTIFY:

- TECHNOLOGY REQUIREMENT
- TECHNOLOGY CATEGORY
- OBJECTIVE ADVANCEMENT REQUIRED
- CURRENT STATE OF ART
- DESCRIPTION OF TECHNOLOGY
- RATIONALE AND ANALYSIS
- TECHNOLOGY OPTIONS
- TECHNICAL PROBLEMS
- POTENTIAL ALTERNATIVES
- PLANNED PROGRAMS
- RELATED TECHNOLOGY REQUIREMENTS
- TECHNOLOGY REQUIREMENTS SCHEDULE
- USAGE SCHEDULE
- REFERENCES

SECTION 3.0
AUTOMATED FAULT DETECTION/ISOLATION AND SYSTEM CHECKOUT

The automated fault detection/isolation and system checkout required technology development for ground processing can be resolved through analyses, simulation and ground testing.

The required technology developments for space processing (same as ones for the ground) can for the most part be resolvd through analyses, simulation and ground testing.

- No testing required on a Shuttle Sortie or ELV
- May want to include some prototype equipment on maintenance/ servicing/support equipment Space Station TDM

Figure 3-1 describes the proposed technology development plan for analysis and ground testing for this technology. It includes a detailed schedule for the tasks to be performed and the cost per year to perform the tasks.

FIGURE 3-1

AUTOMATED FAULT DETECTION/ISOLATION AND SYSTEM CHECKOUT

TECHNOLOGY CATEGORY

- GROUND ANALYSIS & TESTING

OBJECTIVE ADVANCEMENT REQUIRED

- FULLY AUTOMATED GROUND AND SPACE-BASED CHECKOUT, PRELAUNCH PROCESSING, AND LAUNCH PROCESSING OF UPPER STAGES

CURRENT STATE OF ART

- CENTAUR COMPUTER CONTROLLED LAUNCH SYSTEM (CCLS) AND KSC LAUNCH PROCESSING SYSTEM AND MANUAL OPERATIONS (OPERATIONAL) - AUTOMATED THOSE THINGS THAT CAN'T BE DONE MANUALLY
- LIQUID OXYGEN EXPERT SYSTEM (LES) AND KNOWLEDGE - BASED AUTOMATED TEST EQUIPMENT (DEVELOPMENT KSC)

FIGURE 3-1

AUTOMATED FAULT DETECTION/ISOLATION AND SYSTEM CHECKOUT (Continued)

DESCRIPTION OF TECHNOLOGY ELEMENTS REQUIRED

- SMART SENSORS
- BUILT-IN-TEST - EXTEND TO SUBSYSTEMS OTHER THAN AVIONICS
- ON BOARD FAULT ISOLATION/SELF TEST - EXTEND TO OTHER SUBSYSTEMS OTHER THAN AVIONICS
- ARTIFICIAL INTELLIGENCE
  - SEARCH, PROBLEM-SOLVING AND PLANNING
  - COMPUTER VISION
  - EXPERT SYSTEMS
  - ROBOTICS
- AVIONICS ARCHITECTURE
  - VHSIC
  - ADA
  - HIGH SPEED DATA BUSES
  - FIBER OPTIC BUSES

FIGURE 3-1

AUTOMATED FAULT DETECTION/ISOLATION AND SYSTEM CHECKOUT (Continued)

RATIONALE AND ANALYSIS

- NEED TO AUTOMATE TASKS WHICH MIGHT BE EASY OR EVEN PREFERABLE TO DO MANUALLY BUT DON'T WANT TO DO MANUALLY IN SPACE
- MANY TASKS ARE CHEAPER TO DO BY MACHINE
- MUST AUTOMATE TASKS SUCH AS (DONE MANUALLY IN CCLS)
  - SOFTWARE GENERATION/MODIFICATION
  - QUALITY ASSURANCE
  - ANOMOLY TROUBLE-SHOOTING
  - BUY-OFF
  - DATA ANALYSIS
  - DATA STORAGE

TECHNOLOGY OPTIONS

- HIGH DEGREE OF BIT VS LOW DEGREE OF BIT
- SMART SENSORS VS DUMB SENSORS
- MANY SENSORS VS FEW SENSORS
- RELIABILITY/AVAILABILITY OF VEHICLE VS SOPHISTICATION OF SUPPORT EQUIPMENT
- PARTITIONING OF CHECKOUT ON-BOARD VS ON-STATION VS ON-GROUND
- DIFFERENT STRATEGIES FOR DIAGNOSTIC REASONING

FIGURE 3-1

AUTOMATED FAULT DETECTION/ISOLATION AND SYSTEM CHECKOUT (Continued)

TECHNICAL PROBLEMS

This is a systems problem as much as specific technology problem. There is a pitfall here similar to that encountered when trying to implement multiple string redundancy. If the reliability of the active elements and the voting and switching elements is not sufficiently high to begin with, the additional hardware required over single string will actually decrease the reliability instead of increasing it. The danger is that the increased hardware and software to accomplish AI functions and BIT must be well thought out or trouble will result. For example, BIT hardware never increases reliability. It actually increases availability, but always with a penalty of decreased reliability.

Artificial Intelligence has had great promise but delivered little for many years. The resources required for AI are often staggering -- running to megabytes of memory and hugh chunks of CPU time. New hardware such as LISP on a Chip and parallel processing may alleviate this problem, but the hardware must improve further to fully support the concepts.

This type of technology seems to be more easily implemented in avionics systems than in fluids, mechanical and structural systems. Although work remains in avionics, we are finding that the greatest automation payoff will occur non-avionic systems checkout.

POTENTIAL ALTERNATIVES

A high degree of automation is mandatory for the space station. There are no viable alternatives.

FIGURE 3-1

AUTOMATED FAULT DETECTION/ISOLATION AND SYSTEM CHECKOUT (Continued)

PLANNED PROGRAMS OR UNPERTURBED TECHNOLOGY ADVANCEMENTS

- Space Station Development

RELATED TECHNOLOGY REQUIREMENTS

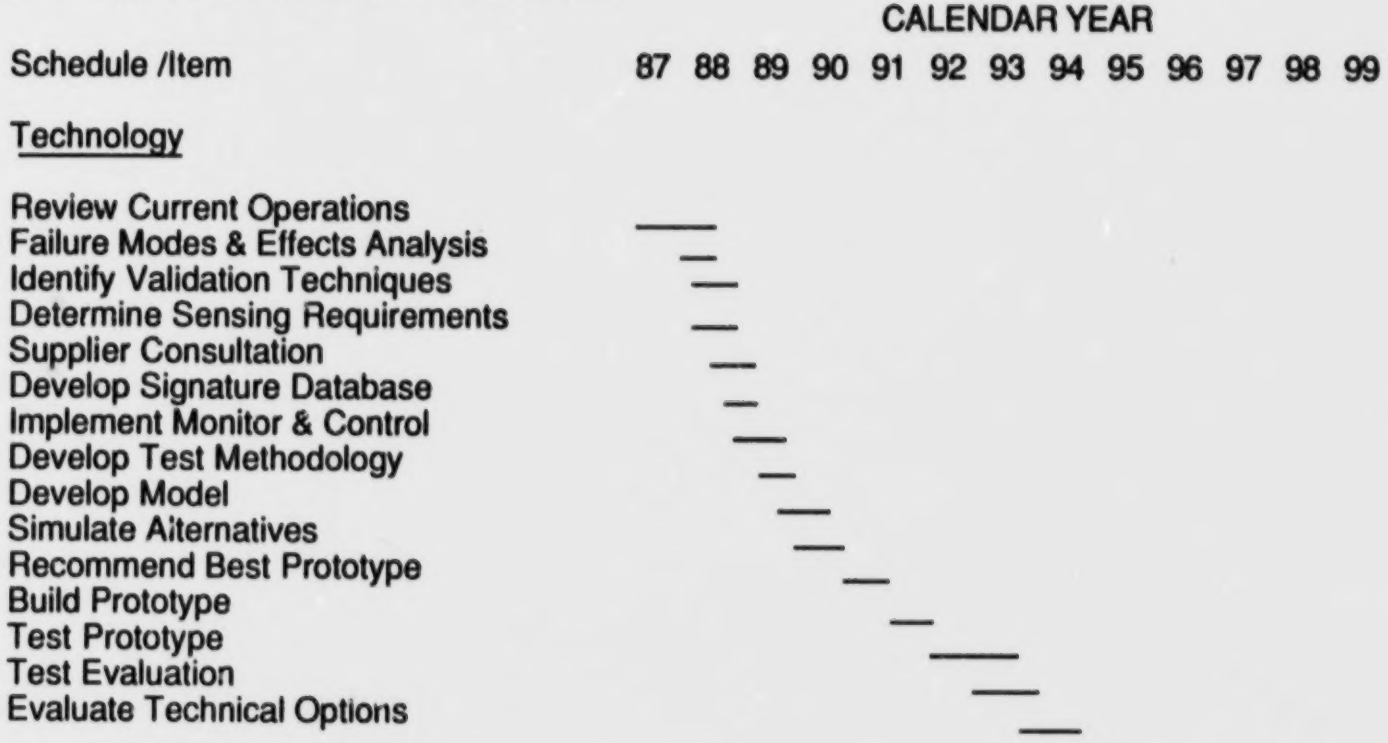
- OAST Generating Technology Development Plan for on-orbit cryogenic depot.

NOTE: No testing required on a Shuttle Sortie or ELV.
May want to include some prototype equipment on maintenance/servicing Space Station TDM.

FIGURE 3-1

AUTOMATED FAULT DETECTION/ISOLATION AND SYSTEM CHECKOUT (Continued)

TECHNOLOGY REQUIREMENTS SCHEDULE



9/29/87
6-6

SECTION 4.0
CRYOGENIC PROPELLANT TRANSFER, STORAGE, AND RELIQUEFACTION

As stated in Section 2.0 we have identified this area as needing development for orbital operations in our previous studies. In addition, OAST sponsored an On-Orbit Cryogenic Depot Technology Task Force meeting in Cleveland, Ohio on September 17 and 18, 1987. This was attended by both NASA and industry personnel. The meeting was called to provide inputs for a "Technology Road Map" for the orbiting depot system which OAST will generate in the near future.

Figure 4-1 lists the requirements for the proposed technologies to be developed. These aren't all inclusive for the cryogenic propellant system as those requirements were identified by LeRC at another time. GD has used this data as a checklist for the technology development plan being generated on this study. Some areas such as water electrolysis is not being considered for near future application.

Figure 4-2 summarizes the key technology groups which must be developed to support the OTV propellant management objectives, and also which of these items require orbital, low-g testing as well as analysis and ground testing.

FIGURE 4-1

ON-ORBIT CRYOGENIC DEPOT TECHNOLOGY DEVELOPMENT ISSUES *(Listed in the chronological order given) 9/17/87

- Tank Development
  - Thermal conductivity
  - Structures
- Automated coupling/decoupling
- Ability to construct large scale tankage on orbit
- Leak detection
- In-situ propellant production
- Water electrolysis
- Automated health monitoring
- Attitude control of dynamic systems
- Total systems engineering
- Safety: fire and contaimination control
- Vibration control
- Tribology issues of on-orbit coupling
- Low gravity heat transfer
- Liquid-vapor separation for microgravity venting
- Microgravity fluids modeling
- Automated operations
  - Rendezvous
  - Proximity operations (docking, berthing)
  - Traffic management
  - Collision avoidance
- Artificial gravity generation
- Repair and maintenance - telerobotics (insulation related problems)
- Advanced insulation
- Advanced refrigeration
- Safety contingencies

*Presented at Cryogenic Depot Technology Work Shop - LeRC - Data generated for long term depot to support Lunar and Mars missions. Some data not applicable to OTV accommodations.

9/29/87
1-2

FIGURE 4-1 (Contd)

ON-ORBIT CRYOGENIC DEPOT TECHNOLOGY DEVELOPMENT ISSUES *(Listed in the chronological order given) 9/17/87 (Contd)

Liquifaction
Lean burning H-O thrusters
Space power
Micrometeoroid/debris protection of large pressure vessels
  Tolerances
  Repair
Materials characterization related to long term failure at low temperatures
Recertification
Multi-stage compressors (>1000 psi) for on-orbit use
Depot compatibility with nuclear radiation
Tether technology

Artificial Intelligence/Expert Systems
Atomic Oxygen Effects on M.L.I.
Zero-G Mass Gaging of Prop. Tanks Flow Meter
Advanced Assembly Methods
  - (Insulation problems)
  - Vis-a-vis spent E.T.'s
On-Orbit Refurbishment
  - Prevention
  - Operations
Automated Ground Support/Processing
Orbital Operation
  - Rendezvous
  - Prox. Operations

*Presented at Cryogenic Depot Technology Work Shop - LeRC - Data generated for long term depot to support Lunar and Mars missions. Some data not applicable to OTV accommodations.

FIGURE 4-2

GENERAL DYNAMICS
Space Systems Division

CRYOGENIC PROPELLANT TRANSFER, STORAGE AND RELIQUEFACTION MANAGEMENT SUMMARY

MANY OTV STORAGE, TRANSFER, AND RELIQUEFACTION TECHNOLOGY PERFORMANCE CAN BE RESOLVED THROUGH ANALYSIS AND GROUND TESTING

- o ACTIVE COMPONENTS (RELIQUEFIER, PUMPS, VALVES, COMPRESSORS, RADIATOR)
- o PASSIVE COMPONENTS (MLI, VCS, P-O CONVERTER)

CERTAIN TECHNOLOGIES REQUIRE ORBITAL, LOW-G TESTING

- o TRANSFER
  - LIQUID ACQUISITION DEVICE
  - PRESSURIZATION SYSTEMS
  - MASS GAGING SYSTEMS
  - NO-VENT FILL/REFILL
  - TRANSFER LINE CHILLDOWN
- o LONG-TERM STORAGE ISSUES
  - THERMODYNAMIC VENT SYSTEM
  - STRATIFICATION AND "HOT SPOT" MANAGEMENT
  - MATERIALS DEGRADATION (MLI, SOLAR SELECTIVE COVER, RADIATOR)
- o MICROMETEOROID/DEBRIS SHIELD PERFORMANCE

The technology required to support OTV propellant management may be accomplished with three phases of development (see Figure 4-3). The early stages will consist primarily of analysis and ground testing of certain technologies. Some of the required components and operations, although they can be assessed by ground tests, should also be included in an ELV/orbital experiment (along with many components and operations which require orbital tests). Two such flight experiments are currently in the planning stages, MSFC's Long-Term Cryogenic Storage Facility System Study, and LeRC's Cryogenic on-Orbit Liquid Storage, Acquisition and Transfer), which will address the key propellant management technologies required for the OTV program.

4.1 PROPELLANT TRANSFER TECHNOLOGY ANALYSIS AND GROUND TESTING

A review of the technology development required to support all OTV propellant transfer design/operational requirements is provided in the Figure 4-4. Transfer lines, disconnect, compressors, valves, pumps, and their related operations may be assessed largely through analyses and ground testing. Automation of transfer processes must be demonstrated, for several transfer scenarios. The technical problems that are to be addressed include propellant leakage, mass gaging, low-g chilldown, acquisition/transfer, and pumping. The alternatives (which are not desirable) to the development of this technology are very limited; do not transfer propellants, but instead replace the user (i.e. OTV) depleted tanks with ELV launched "new" full tanks, produce LH2 on-orbit by electrolysis/reliquefaction, or liquefy delivered injected gas within a storage tank. A schedule for the analysis and ground tests to develop transfer technology is also included, and outlines a three year program to be completed in 1991.

FIGURE 4-3

OTV ACCOMMODATIONS STUDY - PROPELLANT TRANSFER, STORAGE, & RELIQUEFACTION

DEVELOP TECHNOLOGY REQUIRED TO SUPPORT OTV PROPELLANT MANAGEMENT

- o ANALYSIS AND GROUND TESTING
- o EXPENDABLE LAUNCH VEHICLE/ORBITAL FLIGHT EXPERIMENT
  - MARSHALL SPACE FLIGHT CENTER'S "LTCSFSS" (LONG-TERM CRYOGENIC STORAGE FACILITY SYSTEMS STUDY) PROGRAM
  - LEWIS RESEARCH CENTER'S "COLD-SAT" (CRYOGENIC ON-ORBIT LIQUID STORAGE, ACQUISITION AND TRANSFER) PROGRAM
- o TECHNOLOGY DEMONSTRATION MISSION AT THE SPACE STATION

M.W. Liggett 9/30/87

"OTV VG-1"

FIGURE 4-4

PROPELLANT TRANSFER TECHNOLOGY ANALYSIS & GROUND TESTING

DESCRIPTION OF TECHNOLOGY:

- o AUTOMATIC, LEAK-FREE OPERATION OF CRYOGENIC TRANSFER LINES AND DISCONNECTS
- o CHILLDOWN BEHAVIOR OF TRANSFER LINES
- o PRECHILL ACCUMULATOR & COMPRESSOR SYSTEM TEST
- o VALVE & TRANSFER PUMP TESTING

RATIONALE & ANALYSIS:

- o SYSTEM REQUIRES FULLY AUTOMATED TRANSFER SYSTEM
- o RELIABILE, LEAK-FREE OPERATION OF DISCONNECTS, PUMPS, VALVES, AND COMPRESSORS

TECHNOLOGY OPTIONS:

- o TRANSFER LINE CONFIGURATIONS; ELV-SS DEPOT TANK, DEPOT-OTV, ET SCAVENGING
- o TRANSFER PRESSURANT SYSTEM; AUTOGENOUS, GHe, GH2, PUMP-FED
- o TRANSFER LINE INSULATION TYPES/INTERNALLY COATED VS. UNCOATED

FIGURE 4-4

PROPELLANT TRANSFER TECHNOLOGY ANALYSIS & GROUND TESTING (CONT'D,

TECHNICAL PROBLEMS:

- o PROPELLANT LEAKAGE/SPILLAGE @ DISCONNECT(S)
- o PERFORMANCE IN LOW-g VS. 1-g (CHILLDOWN/PRECHILL HEAT TRANSFER, PUMP STARTUP, DISCONNECT)
- o OPERATION MUST BE AUTOMATED
- o MASS GAGING
- o CRYOGEN BOILOFF/LOSS DURING CHILLDOWN & TRANSFER

POTENTIAL ALTERNATIVES:

- o NO TRANSFER OPERATIONS, REPLACE USER (i.e. OTV) TANKS WITH ELV LAUNCHED TANKS
- o PRODUCE LH2/LO2 ON-OBIT BY ELECTROLYSIS OF H20 AND RELIQUEFACTION
- o RELIQUEFY INJECTED GAS WITHIN STORAGE/DEPOT TANK

FIGURE 4-4

PROPELLANT TRANSFER TECHNOLOGY ANALYSIS & GROUND TESTING (CONT'D,

PLANNED PROGRAMS OR UNPERTURBED TECHNOLOGY ADVANCEMENT:

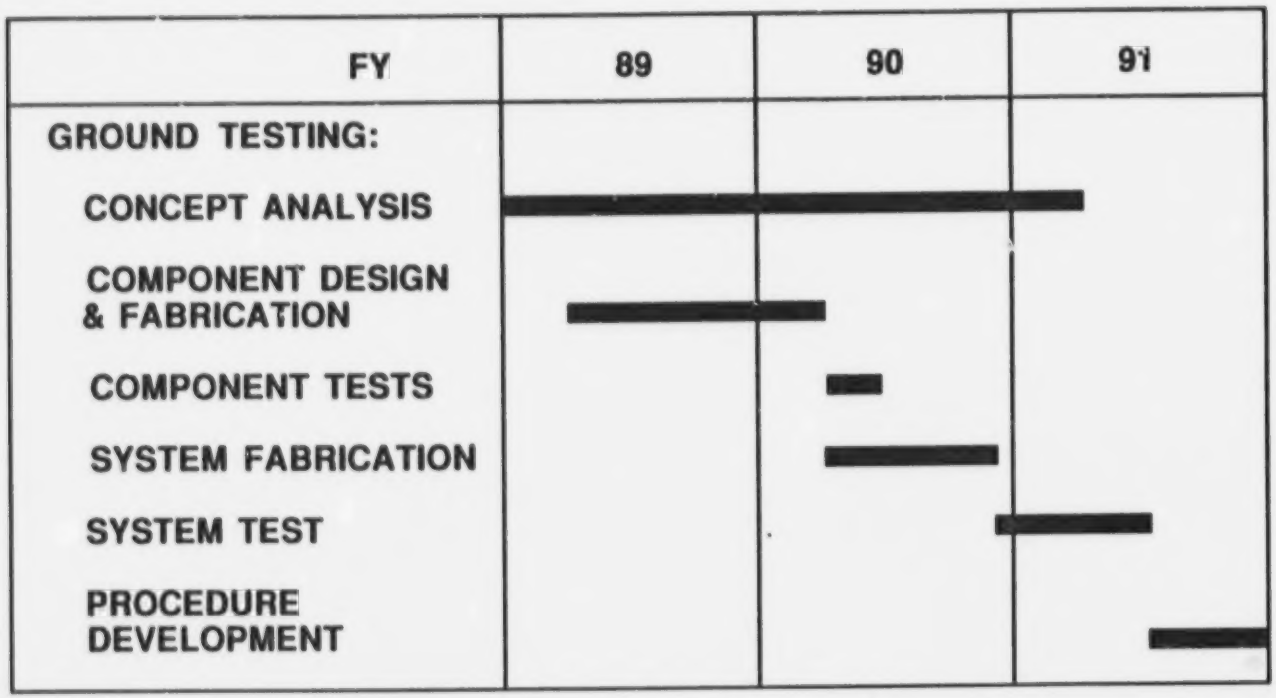
- o MSFC'S "LTCSF" GROUND AND FLIGHT EXPERIMENT PROGRAM
- o LeRC'S "COLD-SAT" PROGRAM

RELATED TECHNOLOGY REQUIREMENT:

- o LONG-TERM CRYOGENIC STORAGE & TRANSFER OF LH2, LO2 FOR BI-PROPELLANT USERS

FIGURE 4-4

OTV ACCOMMODATIONS/SUPPORT HARDWARE FOR PROPELLANT TRANSFER - ANALYSIS AND GROUND TESTING



"OTV VG-5"

M.W. Liggett 9/30/87

4.2 PROPELLANT STORAGE TECHNOLOGY ANALYSIS AND GROUND TESTING

There are also storage technology development issues which must be addressed in order to support the OTV program (see Figure 4-5 for a summary). The listed objectives, justification, and schedule outline the propellant storage technology analysis and ground testing plan. Evaluation of thermal/fluid performance and control subsystem reliability will also support related OTV architecture. The schedule of this development will most likely be driven by NASA's COLD-SAT and LTCSFSS ground test/flight experiment schedules.

4.3 PROPELLANT RELIQUEFACTION TECHNOLOGY ANALYSIS AND GROUND TESTING

In order to provide space-flight qualified refrigeration equipment for use with the OTV architecture, it is necessary to support the development of one or more refrigerators currently under development (see Figure 4-6). The magnetically-suspended Stirling refrigerator, which has been under development at Phillips-Magnavox since 1978, offers the best thermodynamic efficiency of all mechanical cycles for this temperature range, and a single-stage development unit has acquired over 25,000 hours of wear-free, undegraded performance. The need for refrigeration at a propellant storage facility will be driven by numerous factors, including vent/no-vent requirements in the vicinity of the depot, the actual OTV mission model, the cost of propellant delivery to orbit, and the cost/availability of electrical power at the OTV accommodations.

The USAF is planning to use a single-stage (refrigeration at 65K) refrigerator on the AXAF mission in the 1990's. The reliquefaction of LH2 would require a two-stage refrigerator, which has been under development also at Phillips-Magnavox (although the refrigeration stage temperatures are currently classified).

FIGURE 4-5

PROPELLANT STORAGE TECHNOLOGY ANALYSIS & GROUND TESTING

OBJECTIVES:

- o DEVELOP/TEST HARDWARE REQUIRED FOR STORAGE; TANK, SUPPORT STRUTS, MLI, VCS's, P-O CONVERTER, VALVES, TVS, LAD, PRESSURIZATION SYSTEMS
- o EVALUATE STORAGE SYSTEM THERMAL PERFORMANCE
- o EVALUATE CONTROL SUBSYSTEM RELIABILITY

JUSTIFICATION:

- o REQUIRED TO FACILITATE THE OTV ARCHITECTURE AND OPERATION

SCHEDULE:

- o DRIVEN BY THE "COLD-SAT" OR "LTCSFSS" FLIGHT EXPERIMENT SCHEDULES (COLD-SAT PLANNED FOR ~1994 LAUNCH/1996 COMPLETION

FIGURE 4-6

PROPELLANT RELIQUEFACTION TECHNOLOGY ANALYSIS & GROUND TESTING

OBJECTIVES:

- o DESIGN OF RELIQUEFACTION SYSTEM CONCEPTS USING AVAILABLE SPACE-QUALIFIED REFRIGERATOR TECHNOLOGY
  - STIRLING-MAGNETIC (MAGNETIC FIELD SUPPORTS PISTONS)
  - BRAYTONS (ROTARY-RECIPROCATING, AND TURBO BRAYTON)
  - VUILLEUMIER CYCLE
  - MOLECULAR ADSORBTION CYCLE
  - MAGNETIC (A PARA-MAGNETIC MAT'L SUBJECTED TO A CHANGING FIELD)
- o ASSESS THE RELIABILITY, LIFE, AND CONTROL BEHAVIOR OF RELIQUEFIER
- o ESTABLISH SYSTEM CONTROL/PERFORMANCE

JUSTIFICATION:

- o RELIQUEFACTION MAY REQ'D IF BOILOFF VENTING IS NOT PERMITTED
- o ECONOMICS OF THE SYSTEM ARE EFFECTED BY REFRIGERATION

SCHEDULE:

- o STIRLING TECHNOLOGY WILL BE TESTED WITH USAF's AXAF MISSION

4.4 PROPELLANT TRANSFER, STORAGE AND RELIQUEFACTION ORBITAL TEST PROGRAM

This orbital test program approach was developed on the LTCSF study for MSFC to reduce the risk of deploying an orbital cryogenic storage depot (see Figure 4-7). It is based on the depot risk assessment which was performed on that program. The risk reduction efforts required for the depot fell into two categories, those which could be addressed in ground tests and those which required orbital testing. Some of the orbital test issues were being addressed by LDEF, thus were not pursued further. An orbital experiment was defined to address the remaining microgravity-dependent issues. Many of the gravity independent depot features must be included in the orbital experiment to address the microgravity issues. Because of this, the orbital experiment will address many of the depot issues which could have been addressed in ground tests.

All of the OTV propellant storage, transfer, and reliquefaction orbital testing objectives can be met with either of two currently planned NASA programs. Figure 4-8 lists the test objectives outlined for NASA LeRC's COLD-SAT program. The objectives are referred to as the CLASS ONE and CLASS TWO experiment sets. The CLASS ONE set experiments are considered by LeRC to be of higher priority than those listed in CLASS TWO, but there is no priority ranking within the classes.

GENERAL DYNAMICS
Space Systems Division

FIGURE 4-7 DEVELOPMENT OF TEST PROGRAM

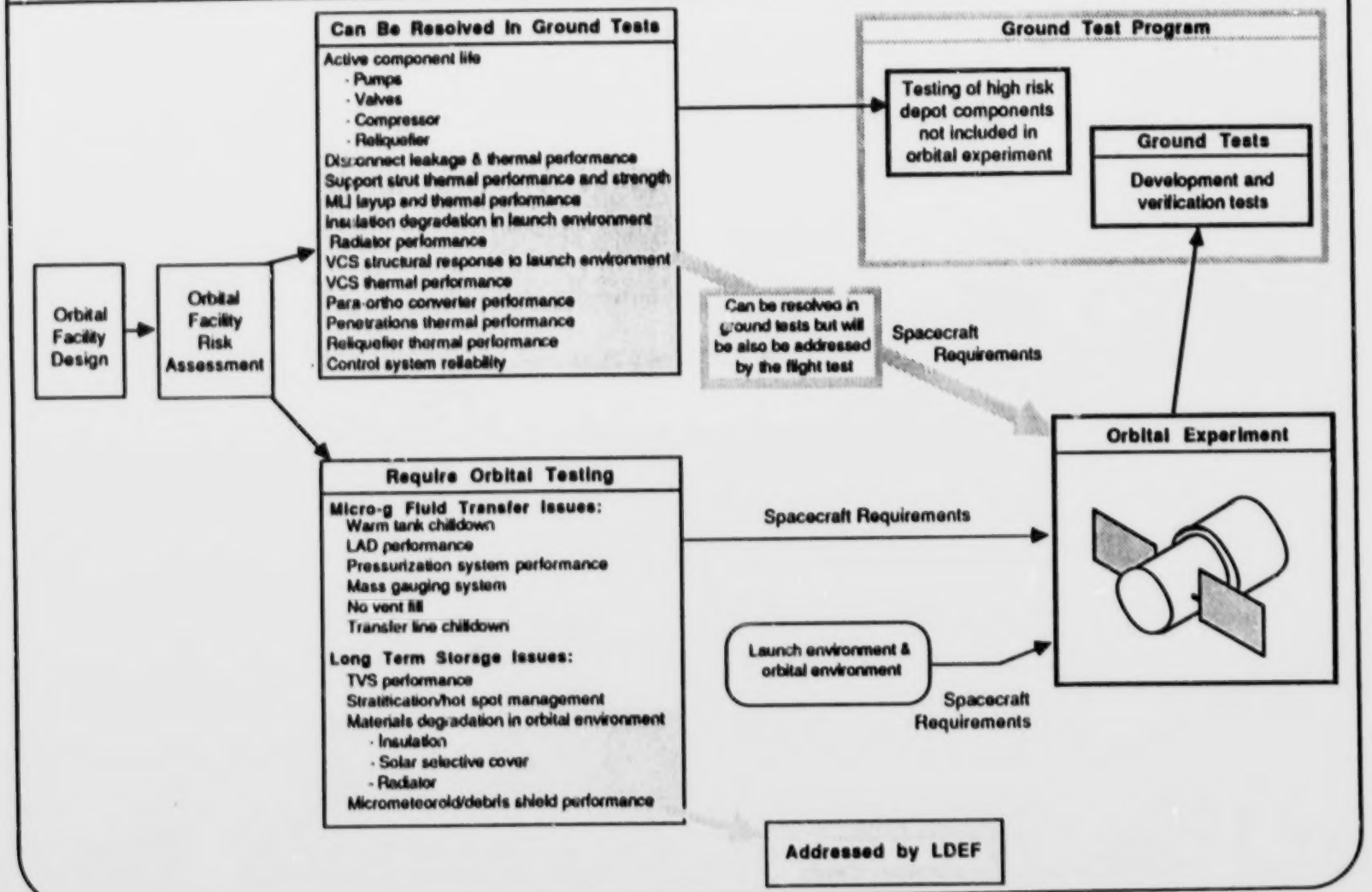


FIGURE 4-8

ELV/ORBITAL TESTING OBJECTIVES

- o CAN BE MET BY MSFC's "LTCSFSS" OR LeRC's "COLD-SAT" PROGRAM
- o COLD-SAT "CLASS ONE" EXPERIMENT SET
  1) PASSIVE, LOW-G CRYOGENIC TANK PRESSURE CONTROL (TVS)
  2) ACTIVE, LOW-G CRYOGENIC TANK PRESSURE CONTROL (TVS & MIXER)
  3) CRYOGENIC TANK CHILLDOWN IN LOW-G (FLUID INJECTED, SPRAY)
  4) NO-VENT FILL/REFILL OF CRYOGENIC TANKS IN LOW-G
  5) FILL OF LAD (LIQUID ACQUISITION DEVICE) IN LOW-G
  6) LOW-G LIQUID MASS GAGING OF CRYOGENIC TANKS
  7) CRYOGENIC LIQUID SLOSH DYNAMICS AND CONTROL IN A LOW-G ENVIRONMENT

FIGURE 4-8 (Contd)

ELV/ORBITAL TESTING OBJECTIVES (CONT'D)

- COLD-SAT "CLASS TWO" EXPERIMENT SET (LOWER PRIORITY THAN CLASS ONE)
  1) EARTH-TO-ORBIT CRYOGEN TRANSPORT "TANKER TANK" THERMAL PERFORMANCE
  2) ORBITAL STORAGE "DEPOT" TANK THERMAL PERFORMANCE
  3) ORBITAL TRANSFER VEHICLE "OTV" TANK THERMAL PERFORMANCE
  4) PRESSURIZATION OF CRYOGENIC TANKAGE IN A LOW-G ENVIRONMENT
  5) DIRECT LIQUID OUTFLOW WITH LOW-G SETTLING
  6) LAD PERFORMANCE IN THE ON-ORBIT ENVIRONMENT
  7) TRANSFER LINE CHILLDOWN UNDER LOW-G CONDITIONS
  8) CONTROL OF FLUID THERMODYNAMIC STATE DURING LIQUID OUTFLOW
  9) LOW-G VENTED FILL OF CRYOGENIC TANKS
  10) ON-ORBIT CRYOGENIC TANKER FLUID DUMPING
  11) ADVANCED INSTRUMENTATION FOR IN-SPACE CRYOGENIC SYSTEMS

GD has identified three development paths that would be taken to develop the cryogenic transfer and storage on orbit. These options are presented on Figure 4-9. Each of these options result in the design, fabrication, and deployment (to LEO) of a full scale propellant depot.

Option 1 uses a 4/10 scale orbital flight experiment, while Options 2 and 3 include a relatively small scale (~1/10 scale) orbital flight experiment. Due to the use of the small scale orbital tests, Options 2 and 3 require intermediate steps prior to the design and deployment of the full scale facility.

Option 2 relies on the ground testing of a full scale LH2 storage tank in a thermal vacuum/thermal balance chamber to provide thermal performane data of the passive and active (reliquefier) thermal control features.

Option 3 includes a full scale LH2/LO2 storage facility TDM at the Space Station, prior to the deplcyment of a full scale propellant storage depot.

Figure 4-10 is a partial list of the critical scaling parameters required in the analysis and design of a cryogenic depot for low-g environments.

A detailed scaling analysis is required to provide an orbital experiment design which addresses key performance parameters. It is difficult, if not impossible to provide a sub-scale test article design which will yield test results that are directly scalable to a larger scale LH2 or LO2 tank. In the final analysis, a test article should be designed to provide good scalability of the components which are deemed critical. This must be done in the near future to keep determine the size of the ELV experiment which will yield enough confidence in the scalability of the results.

FIGURE 4-9

GENERAL DYNAMICS
Space Systems Division

OTV ON-ORBIT PROPELLANT STORAGE DEPOT HARDWARE DEVELOPMENT OPTIONS

Three different approaches to the development of an on-orbit cryogenic propellant storage depot have been considered:

OPTION 1: a) Large scale (i.e. 0.40) ELV launched orbital flight experiment

b) Design, checkout and launch of full scale LTCSF

OPTION 2: a) Small scale (i.e. 0.1) ELV launched orbital flight experiment

b) Ground testing of "Protoflight" unit

c) Design, checkout and launch of full scale LTCSF

OPTION 3: a) Small scale (i.e. 0.1) ELV launched orbital flight experiment

b) Space Station TDM with full scale rec'vr tank

c) Design, checkout and launch of full scale LTCSF

M.W. Liggett 10/24/87

"OTV VG-1A"

FIGURE 4-10

GENERAL DYNAMICS
Space Systems Division

OTV PROPELLANT STORAGE DEPOT DEVELOPMENT CRITICAL SCALING RELATIONSHIPS

EXPERIMENT	SIGNIFICANT PARAMETERS
Thermodynamic venting, passive & active	TVS flowrate/direct venting flowrate, tank pressure/vapor pressure, Weber no., jet Reynolds no., mixing parameter (time), Bond no., mixer heat input / total heat input
Tank prechill	Tank pressure, volume/tank mass, temperature, Nusselt no., spray Reynolds no., mixing parameter
No-vent fill	Nusselt no., spray / jet Reynolds no., mixing parameter, peak pressure / vapor pressure, Weber no., Jacob no.
Liquid acquisition device fill / refill	Bond no., liquid volume / total volume, bulk density / liquid density, average bubble volume / total ullage volume
Slosh dynamics & control	Bond no., jet Weber no., acceleration ratios, dimensionless slosh frequency, damping factor, expulsion efficiency

M.W. Liggett 10/13/87

"OTV VG-1.5A"

Figure 4-11 compares the various Long Term Cryogenic Service Facility (LTCSF) experiments with the full scale LTCSF and shows the relative size of the various experiments

4.4.1 OPTION 1

Details of the steps required to complete development Option 1 are outlined on Figure 4-12. The supply tank which holds the LH2 for the flight experiment during launch is oversized to insure that sufficient fluid remains for a complete "tanking" of the receiver tank on orbit under low-g conditions. The experiment mass is such that a Titan IV launch vehicle is required for its' deployment.

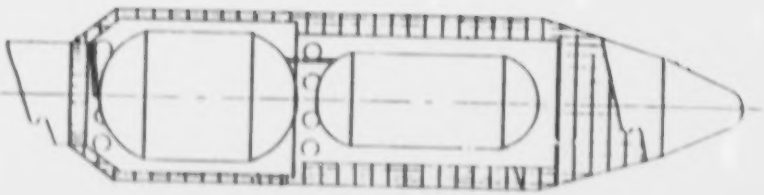
Following the 4/10 scale flight experiment, the design, fabrication, and deployment (to LEO) of the full scale "first article" propellant storage depot will be conducted.

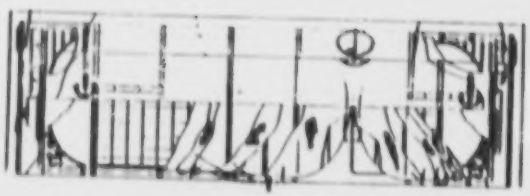
The large scale experiment has the same components as the small scale LTCSF experiment but is substantially larger.

The large scale experiment (see Figure 4-13) has a LH2 launch capacity of 8160 lbs. versus 1440 lbs for the small scale experiment. This will result in more accurate modeling of the full scale LTCSF. However this also results in a total payload weight of 25,000 lbs for the large scale experiment versus 9800 lbs. for the small scale experiment, therefore launch costs will also be significantly more for the large scale experiment.

The large scale experiment is shown in a 66 ft. long 16.5 ft. dia fairing mounted on a Titan IV. It is expected that fairings up to 86 ft. long will be available for this vehicle.

FIGURE 4-11 LTCSF FLIGHT EXPERIMENT OPTIONS





SMALL SCALE (~1/10) ORBITAL FLIGHT EXPERIMENT

Launch Vehicle:	Atlas/Centaur
Experiment Size:	10.5 ft. dia. max., 24 ft. long
LH2 Capacity:	230 cu. ft., 998 lbs. (Receiver Tank)
Total Weight:	~9800 lbs. wet

LARGE SCALE (~4/10) ORBITAL FLIGHT EXPERIMENT

Launch Vehicle:	TITAN IV SS I &II
Experiment Size:	15 ft. dia. max., 47 ft. long
LH2 Capacity:	1320 cu. ft., 5728 lbs. (Receiver Tank)
Total Weight:	~25000 lbs. wet

FULL SPACE STATION LH2 TDM

Launch Vehicle:	Space Shuttle (dry), or SDV
Experiment Size:	14.5 ft. dia. x 34.5 ft. long
LH2 Capacity:	3292 cu. ft., 14286 lbs.
Total Weight:	~18000 lbs. dry

FULL SCALE LONG TERM CRYOGENIC STORAGE DEPOT

Launch Vehicle:	Space Shuttle (dry), SDV or ALS
Size:	14.5 ft. dia. x 50 ft. long
Capacities:	3292 cu. ft. LH2, 1203 cu. ft. LO2
	14286 lbs. LH2, 85714 lbs. LO2
Total Weight:	~30200 lbs. dry

FIGURE 4-12

OTV ON-ORBIT PROPELLANT DEPOT DEVELOPMENT OPTION 1

Development Option 1 consists of two separate phases, the results of the first phase being required for the design of the following phase.

o An orbital experiment:

- Receiver tank is 4/10 scale of the LTCSF LH2 tank
- Supply tank is 1.43 times rec'vr volume (to allow a complete transfer to/filling of the receiver tank and 30% margir for boiloff/transfer losses)
- Experiment requires a Titan IV launch vehicle, due to the payload limitations of the Atlas/Centaur.

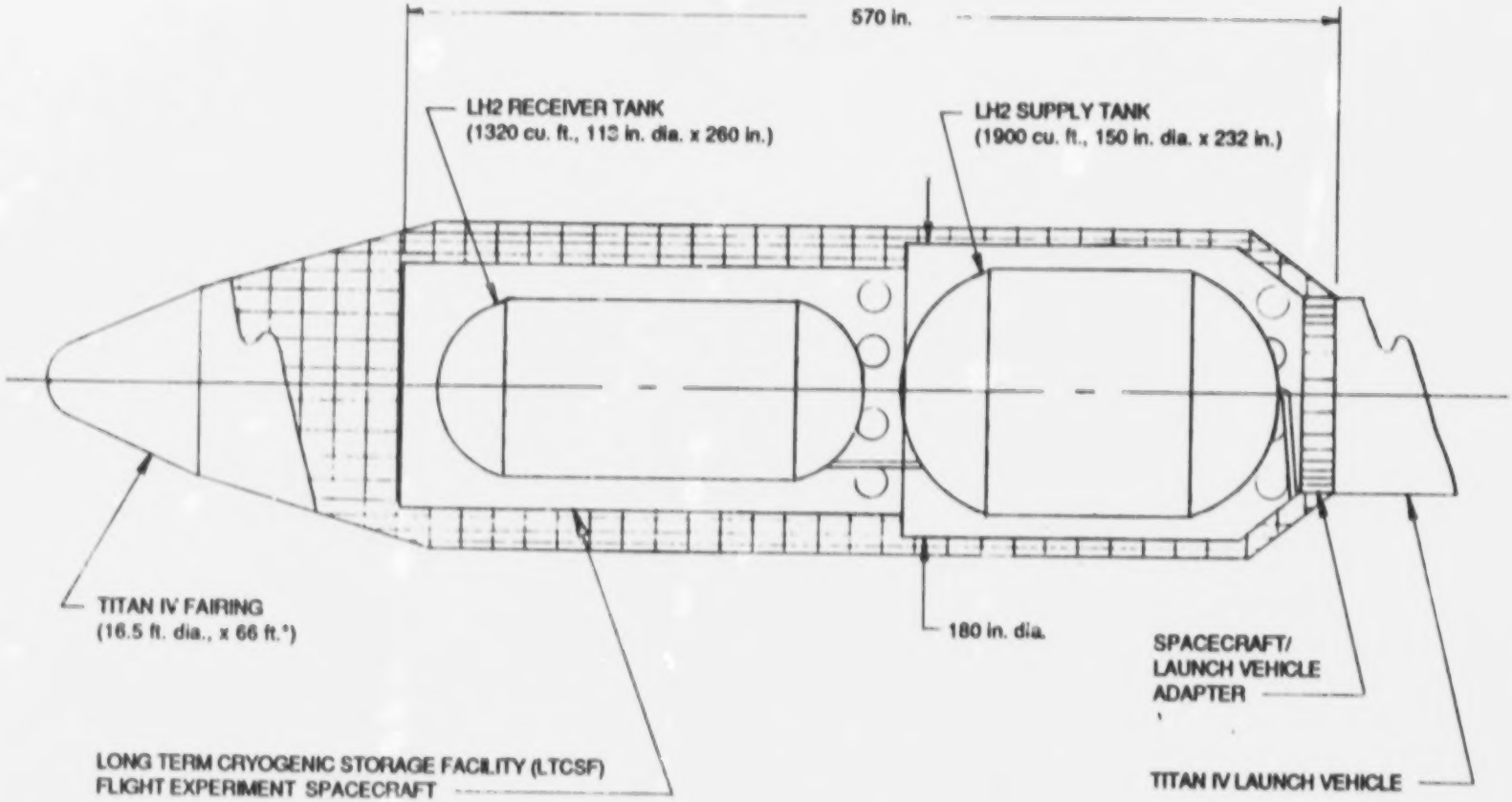
o Design and fabrication of the full scale LTCSF:

- Based on the data gathered from the orbital testing
- Perform qualification/acceptance tests and then launch empty in the STS cargo bay to LEO deployment at the SS.

FIGURE 4-13

GENERAL DYNAMICS
Space Systems Division

LARGE SCALE (~0.4) LTCSF FLIGHT EXPERIMENT (CONFIGURED FOR TITAN IV LAUNCH VEHICLE)



* FAIRINGS UP TO 86 FT. LONG WILL BE AVAILABLE

The operational LTCSF has a 100,000 total storage capacity of LH2 and LO2. The LO2 capacity is approximately 85,700 lbs. and the LH2 capacity is approximately 14,300 lbs. The dry weight of this facility is approximately 30,200 lbs. (See Figure 4-14)

Tank shells for the LH2 and LO2 have cylindrical mid-sectins with elliptical end domes, both of 154 inch diameter, and employ 2219-T87 aluminum alloy. Bulkheads used in this concept are elliptical domes with a ratio of major radius to minor radius of 1.379. Components located internal to the tank shell include a thermodynamic vent system, mass gauges, the liquid acquisition device and fluid baffles. Tank shells are structurally supported to the inner debris/micrometeoroid shield via a system of glass/epoxy composite struts.

Surrounding the primary tank shells is a system of multi-layer insulation blankets and a vapor cooled shield (VCS).

The LTCSF is surrounded by a dual wall aluminum micrometeoroid/debris shield. The inner shell also serves as the primary structural shell typing together the LH2 and LO2 tanks.

Also shown is the reliquefaction equipment that takes boiloff exiting the vapor cooled shields and returns it to the propellant storage tanks as saturated liquid.

4.4.2 OPTION 2

The approach taken in Option 2 (see Figure 4-15) requires that a 1/10 scale, Atlas/Centaur launched flight experiment be followed by a full scale "Protoflight" LH2 tank thermal performance ground test. In addition to the passive (MLI, vapor cooled shields, p-o converters) and active (LH2 space qualified cryogenic refrigeration system) thermal performance tests, limited testing of the Liquid Acquisition Device (LAD) and Thermodynamic Vent System (TVS) may be performed in the 1-g environment.

The results of these two tests will provide a good overall basis for the design of the full scale LTCSF.

FIGURE 4-14

LONG TERM CRYOGENIC STORAGE FACILITY (LTCSF)

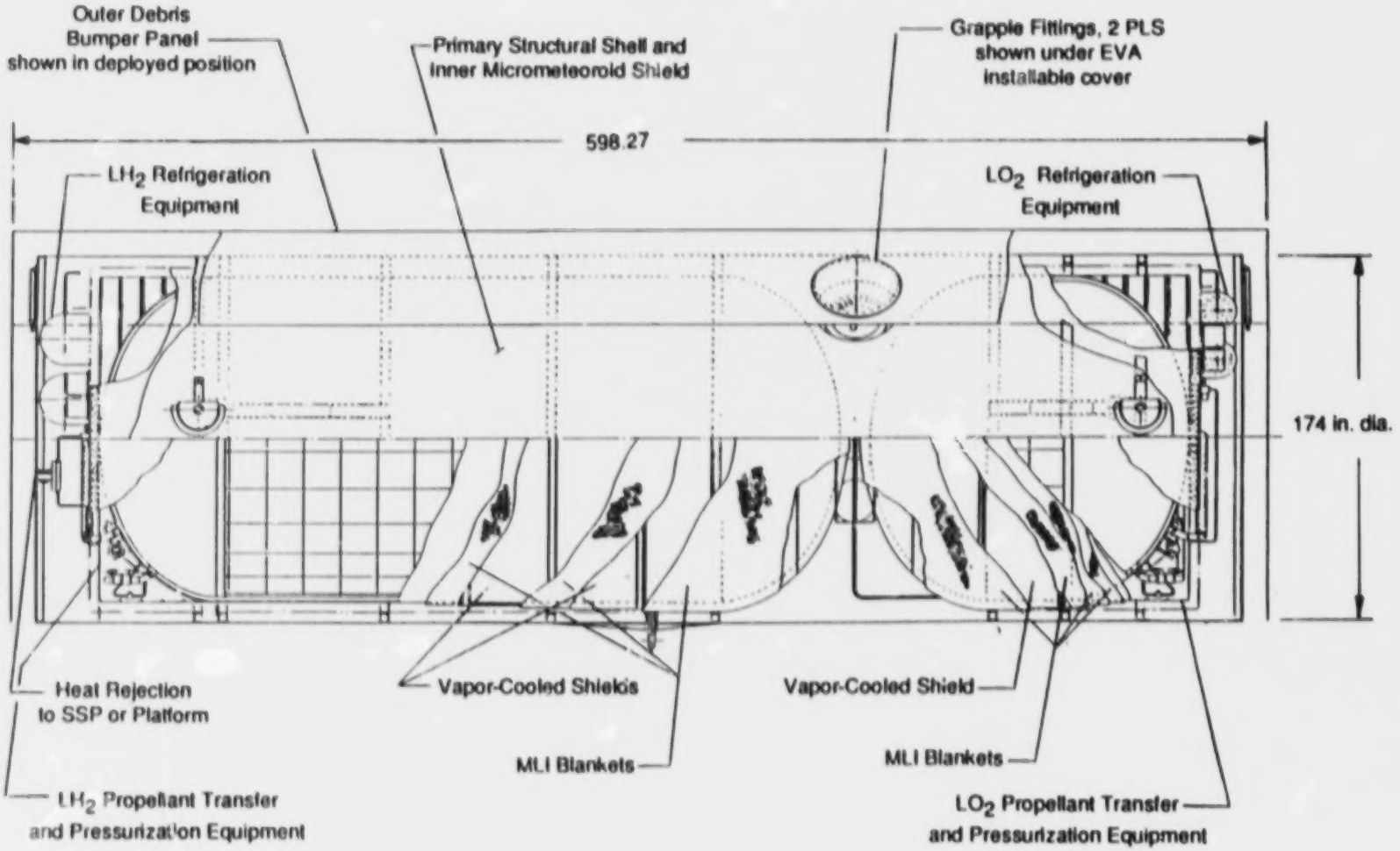

Outer Debris Bumper Panel shown in deployed position
Primary Structural Shell and Inner Micrometeoroid Shield
Grapple Fittings, 2 PLS shown under EVA installable cover
598.27
LH_2 Refrigeration Equipment
LO_2 Refrigeration Equipment
174 in. dia.
Heat Rejection to SSP or Platform
Vapor-Cooled Shields
Vapor-Cooled Shield
MLI Blankets
MLI Blankets
LH_2 Propellant Transfer and Pressurization Equipment
LO_2 Propellant Transfer and Pressurization Equipment

FIGURE 4-15

OTV ON-ORBIT PROPELLANT DEPOT DEVELOPMENT OPTION 2

Option 2 development employs a slightly different approach, requiring three separate phases for its' completion:

- o An orbital experiment:
  - Receiver tank is 1/10 scale of LTCSF LH2 tank
  - Supply tank is 1.43 times the rec'vr volume
- o Ground testing of a full scale "Protoflight" article:
  - Full scale LTCSF LH2 tank thermal performance and 1-g LAD/TVS tests (in a thermal vacuum/balance chamber)
- o Design and fabrication of the full scale LTCSF:
  - Based on the data from the orbital tests and Protoflight tests
  - Perform qualification/acceptance tests and then launch empty in the STS cargo bay to LEO deployment at the SS

M.W. Liggett 10/24/87

"OTV VG-3A2"

Figure 4-16 shows a breakaway side view of an Atlas/Centaur launched LTCSF flight experiment as part of Option 2. The major systems highlighted in this view are the payload fairing envelopes, the RCS hydrazine storage bottles, the dewar assembly, the receiver assembly, the LH2 feed system, the autogenous pressurization system, the GH2 and GHe pressurization system, the reliquefaction system, the control systems, and the tank support struts.

The hydrazine storage bottles (5) and a pressurization bottle are placed at the bottom of the spacecraft due to the vehicle configuration required to fit into the fairing and also to place the vehicle c.g. close to the spacecraft/vehicle interface. These bottles are sized to maintain orbit for two years and also provide a reserve to perform additional maneuvers required by the experiment.

The dewar assembly consists of an inner fluid vessel, 2 layers of MLI, a vapor cooled shield, 2 layers of MLI, a vacuum gap and a vacuum shell. The receiver assembly consists of a LH2 tank, 3 MLI blankets, and 2 vapor cooled shields.

The LH2 fluid system includes the fill and drain lines, the tank transfer liens, and the vent line. The fill and drain line is located at the aft end of the vehicle to allow draining of the LH2 in case the mission is aborted before launch.

The tank pressurization consists of several systems. The heat exchanger/pump assembly is used to draw off LH2 from the receiver and convert it to GH2 for receiver pressurization. The GH2 bottles proven warm vapor pressurization and the GHe bottles are used as backups.

The reliquefaction system includes the reliquefier and two accumulators for gas storage.

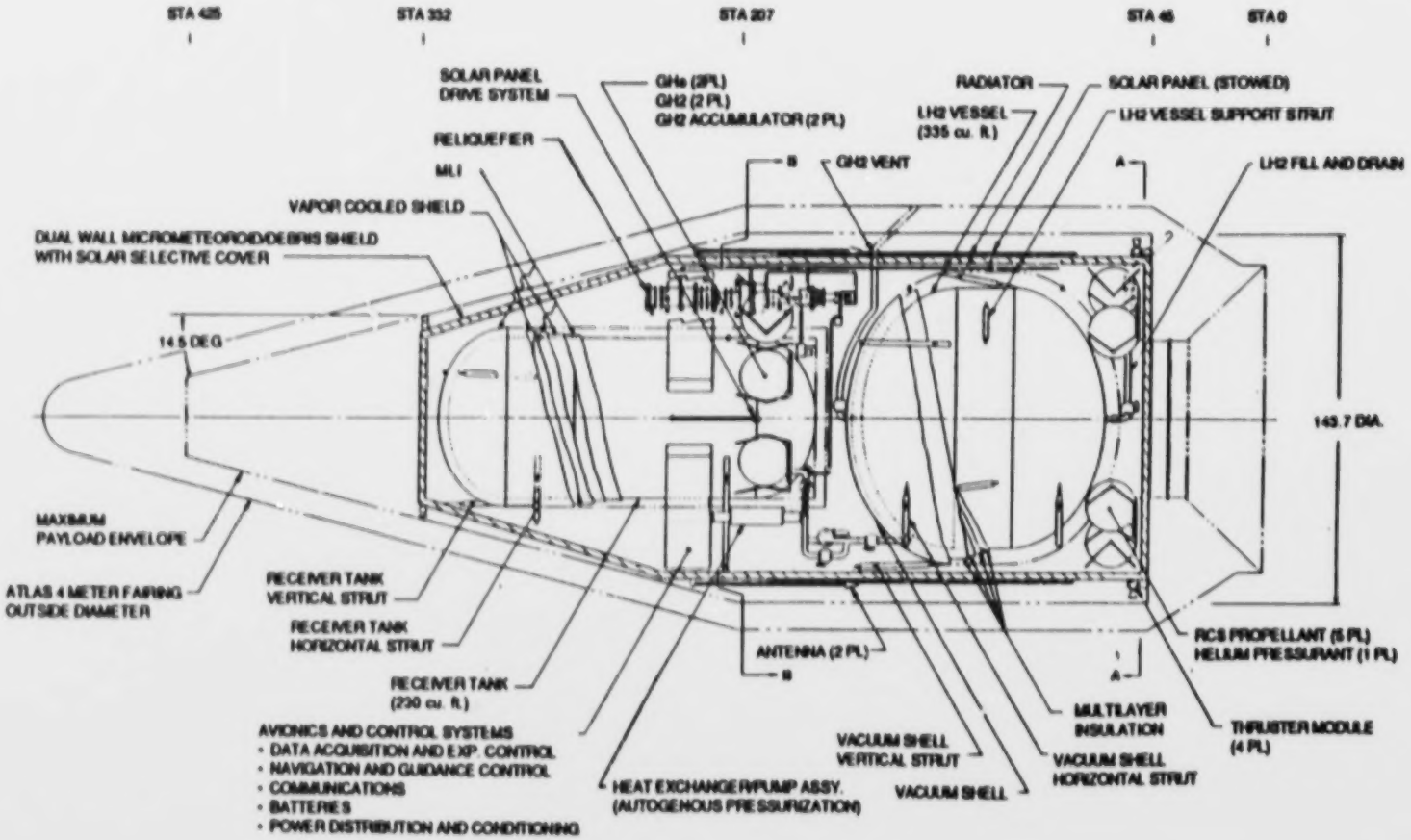
A complete configuration definition of the control system has not yet been accomplished, therefore only a volume allocation is provided on the drawing.

The tank support strut sizes and orientations were chosen based on vehicle geometry, minimization of heat losses, and to account for tank contracion and expansion during fill and drain operations.

FIGURE 4-16

GENERAL DYNAMICS
Space Systems Division

SMALL SCALE (~1/10) LTCSF FLIGHT EXPERIMENT (CONFIGURED FOR ATLAS/CENTAUR LAUNCH VEHICLE)



SIDE VIEW

ALL DIMENSIONS IN INCHES

The protoflight unit consists of a full scale LTCSF LH2 tank and all associated equipment and structure with the exception of the micrometeoroid/debris shield (see Figure 4-17). The LO2 tank and supporting equipment and structure are removed and replaced by a panel with a fluid coolant. LH2 is used in the protoflight unit because the technical challanges of LH2 storage/transfer are greater than those for LO2.

The thermal vacuum/balance chamber shown is similar in size to an existing one located at the Arnold Engineering Development Center in Tullahoma, Tenn.

Ground tests with the protoflight article will allow for the prediction of the LTCSF LH2 system orbital thermal performance.

4.4.3 OPTION 3

The sequence of development steps for Option 3 (see Figure 4-18) uses a 1/10 scale (identical to Option 2, with the possible exception of minor design differences to insure scalability of the predetermined critical parameters) flight experiment, and a full scale LH2 tank and reliquefaction system TDM (STS bay launched) at the Space Station to facilitate the confident design of the full scale depot.

The final phase is identical to Options 2 and 3, which results in the deployment of the full scale LTCSF.

Figure 4-19 shows the size of a full scale LH2 LTCSF tank that could be used as LTCSF TDM at the Space Station. It is identical to the LTCSF except that the LO2 tank and all associated structure and equipment are deleted.

This experiment can be launched in the Shuttle, Shuttle derived vehicle, or Titan IV.

LH2 is used in the TDM because the technical challanges of LH2 storage/transfer are greater than those for LO2.

FIGURE 4-17

"PROTOFLIGHT" ARTICLE LH2 TANK IN THERMAL VACUUM/BALANCE CHAMBER

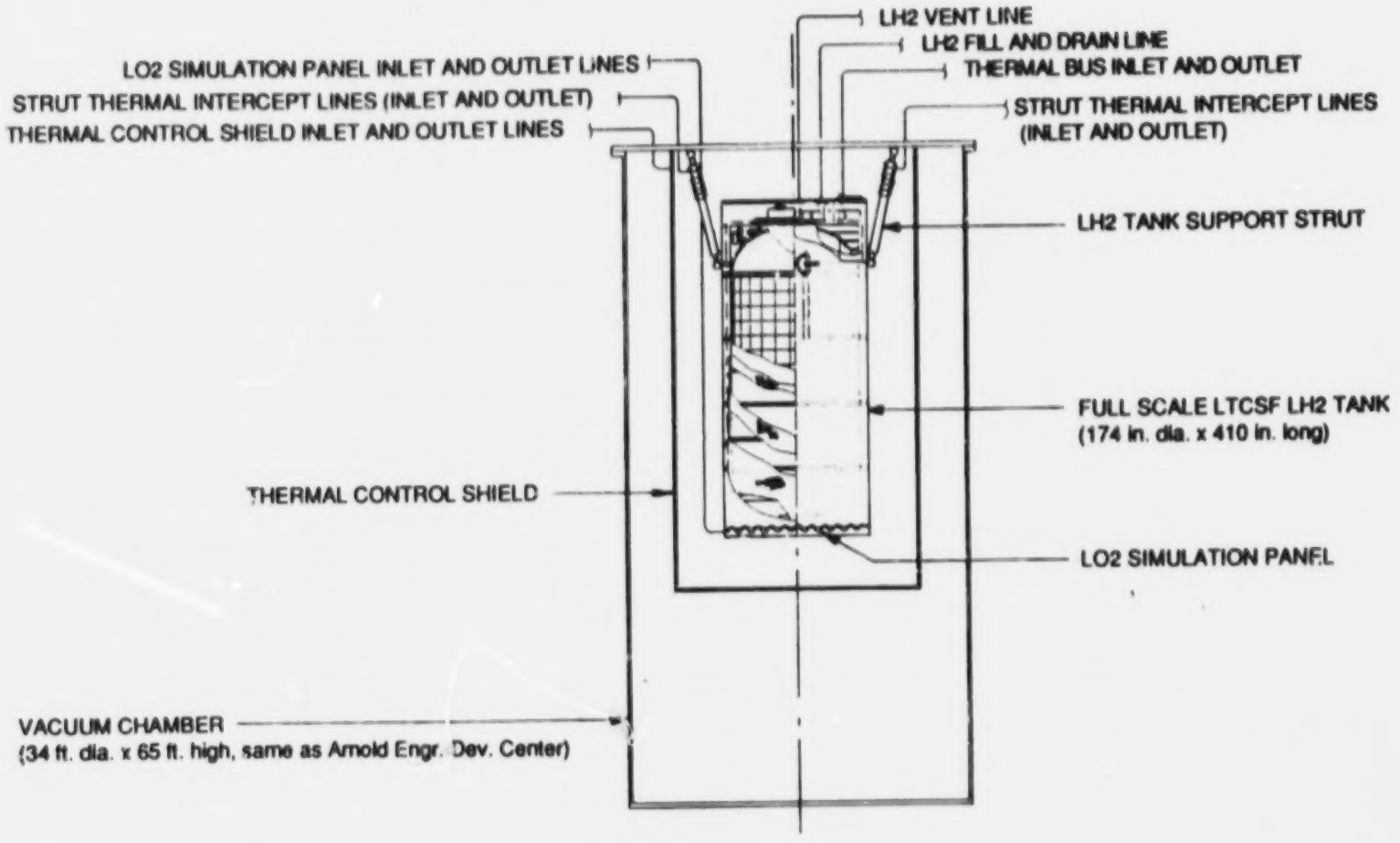

LH2 VENT LINE
LH2 FILL AND DRAIN LINE
LO2 SIMULATION PANEL INLET AND OUTLET LINES
THERMAL BUS INLET AND OUTLET
STRUT THERMAL INTERCEPT LINES (INLET AND OUTLET)
STRUT THERMAL INTERCEPT LINES (INLET AND OUTLET)
THERMAL CONTROL SHIELD INLET AND OUTLET LINES
LH2 TANK SUPPORT STRUT
FULL SCALE LTCSF LH2 TANK (174 in. dia. x 410 in. long)
THERMAL CONTROL SHIELD
LO2 SIMULATION PANEL
VACUUM CHAMBER (34 ft. dia. x 65 ft. high, same as Arnold Engr. Dev. Center)

FIGURE 4-18

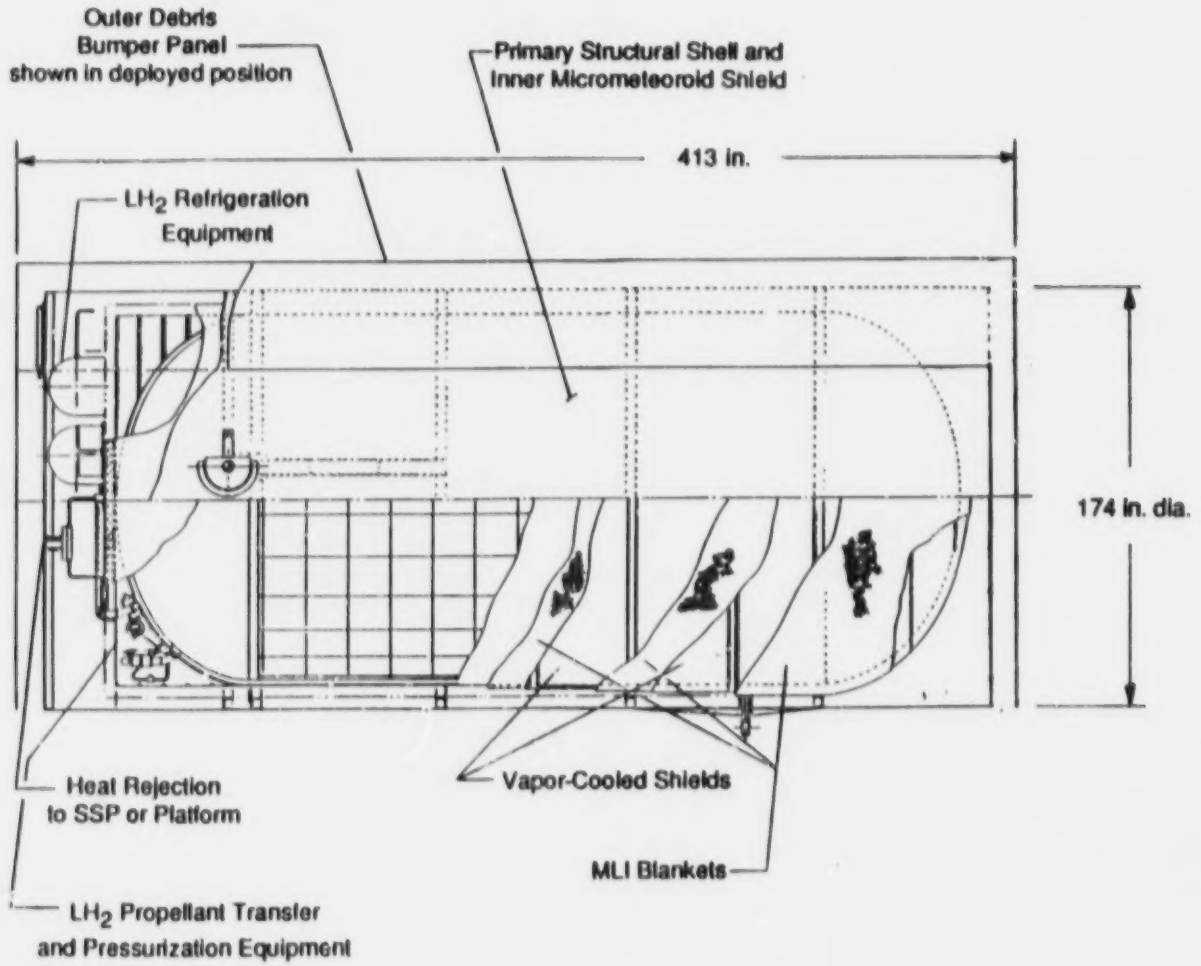
OTV ON-ORBIT PROPELLANT DEPOT DEVELOPMENT OPTION 3

The development of depot technology using a third approach includes a Technology Demonstation Mission at the Space Station prior to the deployment of a full scale LTCSF.

- o An orbital experiment 1/10 scale (identical to that flown in option 2)
- o This phase comprises the TDM:
  - A full scale, LTCSF sized LH2 receiver tank, delivered to the SS by the Shuttle
- o The third pase is identical to the final phases of Options 1 and 2, and completes the development of OTV propellant storage technology with the delivery of a full scale LTCSF.

FIGURE 4-19

FULL SCALE LTCSF LH2 RECEIVER TECHNOLOGY DEVELOPMENT MISSION (TDM) AT THE SPACE STATION



4.4.4 COMPARISON OF THE OPTIONS

Figure 4-20 shows the ROM costs of the elements of the OTV propellant development options. Shuttle launch costs are not shown because theyu would be the same to get all the hardware to the Space Station. The ELV launch costs are included because they ae different for the different launch vehicles.

Figure 4-21 shows the total ROM development costs for the three options.

GENERAL DYNAMICS
Space Systems Division

FIGURE 4-20

OTV PROPELLANT DEVELOPMENT OPTIONS ROM COSTS

		1/10 SCALE TEST	4/10 SCALE TEST	PROTOFLIGHT GR TESTS (LH2 ONLY)	TDM* (LH2 ONLY)	DEVELOP OF* LTCSF AFTER TDM	LTCSF* (LH2 & LO2)
COST (87M$)	NR	159	181	61	296	190	371
	R	37	45	--	60	38	75
	ELV	60	98	--	--	--	--
	OPS	--	--	--	--	--	--
		256	324	61	356	228	446

*SHUTTLE LAUNCH COSTS EXCLUDED

11/87

FIGURE 4-21

GENERAL DYNAMICS
Space Systems Division

COMPARISON OF OTV ON-ORBIT PROPELLANT DEPOT DEVELOPMENT OPTIONS - COST ($M)

	4/10 SCALE TEST		LTCSF				
OPTION #1	324	+	446	≃	770		
	1/10 SCALE TEST		GR TEST (LH2 ONLY)		LTCSF		
OPTION #2	256	+	61	+	446	≃	763
	1/10 SCALE TEST		TDM (LH2 ONLY)		REMAINING LTCSF DEV		
OPTION #3	256	+	356	+	228	≃	840

11/87

Figure 4-22 summarizes the advantages and disadvantages of the three development program Options.

The main advantage of the Option 1 is that the large scale orbital flight experiment will provide "better" scaling data than the 1/10 scale orbital tests used in Options 2 and 3. This may eliminate the need for an intermediate test program.

The primary advantage of the second Option is due to the fact that a relatively low cost flight experiments followed by a large scale ground test which will provide a good understanding of full scale thermal performance.

Figure 4-23 highlights the important conclusions, and emphasizes the fact that the decision of a development program will most likely be driven by cost, schedule, and relative technological risks of each Option. More detailed analyses is required to develop this data to the level required to make a recommendation. Therefore, a recommendation can't be made at this time.

FIGURE 4-22

GENERAL DYNAMICS
Space Systems Division

COMPARISON OF OTV ON-ORBIT PROPELLANT DEPOT DEVELOPMENT OPTIONS

	ADVANTAGES	DISADVANTAGES
OPTION 1: a) 4/10 scale orbital exp. b) Full scale LTCSF	o "Large" scale orbital test, which allows scalability of some critical parameters required for the full scale LTCSF design (rec'vr tank m/V 's ~ equal). o No intermediate test program, allows for more aggressive development schedule	o Requires scaling from 4/10 to full scale o Requires Titan IV launch vehicle for deployment of the orbital experiment, more expensive than Atlas/Centaur.
OPTION 2: a) 1/10 scale orbital exp. b) Protoflight ground test c) Full scale LTCSF	o Lower cost orbital experiment, only a single Atlas/Centaur launch required for test program. o Scalability of thermal performance from Protoflight ground test to full scale LTCSF	oScaling of transfer phenomenon from 1/10 scale to full scale LTCSF (m/V ~2.5 x m/V full scale rec'vr tank) still leaves uncertainties in modeling o Requires Protoflight ground testing of 3-6 months to provide full scale thermal performance data base.
OPTION 3: a) 1/10 scale orbital exp. b) TDM @ SS c) Full scale LTCSF	o Provides the highest degree of confidence for the design of the full scale LTCSF for OTV accomodations.	o Requires Technology Demonstration Mission, which results in higher program development cost. o Development schedule risk to meet IOC

FIGURE 4-22 SUMMARY OF OTV ON-ORBIT PROPELLANT DEPOT DEVELOPMENT PROGRAM

GENERAL DYNAMICS
Space Systems Division

Each of the three options has advantages and disadvantages, and the decision will be driven by the development program cost/funding schedule and the technological risk impacts on the OTV program.

	Schedule Impact	ROM Cost Impact
OPTION 1 provides a moderate degree of scalability at a moderate program cost.	Best	$770
o Large (4/10) scale initial orbital experiment provides the best basis for scaling of transfer, storage, and reliquefaction behavior to the design of the full scale LTCSF.		
OPTION 2 provides a moderate degree of scalability.	Moderate	$763
o Scalability of reliquefaction and some storage phenomenon are roughly equal to that provided by OPTION 3.		
o Lowest scalability of transfer phenomenon (from 1/10 scale to full scale) of any of the three options.		
OPTION 3 provides the highest degree of full scale depot facility design confidence, at the highest program cost.	Greatest	$840
o Requires TDM for scalability of transfer, storage, and reliquefaction performance to the full scale LTCSF.		

CAN'T MAKE RECOMMENDATIONS AT THIS TIME

"OTV VG-6A2"

M.W. Liggett 10/24/87

SECTION 5.0
OTV MAINTENANCE/SERVICING OPERATIONS AND SUPPORT EQUIPMENT TECHNOLOGY

Many OTV maintenance/servicing/operations and support equipment required technology developments can be resolved through analysis, simulation and ground testing.

- o Teleoperations/robotics/tools
- o Crewman support/workstation/translation equipment
- o OTV translating and berthing rotation equipment
- o Control/displays/communications

Certain technologies require orbital, low-g testing

- o EVA maintenance/servicing operations/controls/tools
- o Teleoperations/robotics/controls/tools (verification)

5.1 OTV MAINTENANCE/SERVICING OPERATIONS AND SUPPORT EQUIPMENT TECHNOLOGY ANALYSIS AND GROUND TESTING

OTV Maintenance and Servicing in space are essential elements for successful deployment and continued operation of a Space-based OTV. This assessment of technology development needs defines necessary equipment, operational scenario development, and ground testing required to proof the concepts to support OTV turnaround operations in space. The Shuttle Sortie and Space Station TDM are covered in the next sections.

5.1.1 OTV MAINTENANCE AND SERVICING OPERATIONS AND SUPPORT EQUIPMENT

The question of what maintenance/servicing tasks can be accomplished mroe effectively by EVA or by a remote control arm (automatic and man-in-the-loop operation) must be investigated. The EVA operations development has been addressed in Section 5.1.2. Analysis must be performed to determine the candidate maintenance/servicing tasks for automated operation. Then simulations and ground tests need to be performed to determine the requirements for the automated equipment and the OTV equipment being maintained/serviced. GD feels that the recommended automated equipment approach should be tested on a Shuttle Sortie mission to make sure that the zero-g aspects are fully understood.

In addition to the remote control arm equipment, other maintenance facilities/equipment must also be developed such as the engine removal support equipment, the crewmen translation equipment and the OTV translating and berthing rotation equipment. Analysis and ground tests need to be conducted in each of these areas to develop the concepts and the critical components that would be affected by zero-g need to be tested in a Shuttle sortie mission.

Figure 5-1 defines the technology development needs for the support equipment. Figure 5-1a shows the analysis, simulation and ground testing for the support equipment and EVA operations combined.

FIGURE 5-1
OTV MAINTENANCE AND SERVICING TECHNOLOGY DEVELOPMENT

OBJECTIVES ADVANCEMENT REQUIRED:

- MAINTAIN/SERVICE OTV AT SPACE STATION USING TELEOPERATIONS/ROBOTICS
- EVA OPERATIONS FOR CONTINGENCIES

CURRENT STATE OF ART:

- EVA ACTIVITY IN SHUTTLE WITH CURRENT SPACE SUIT
- SOME TELEOPERATIONS HANDLING AND EVA TRANSLATION

DESCRIPTION OF TECHNOLOGY:

DEVELOP CAPABILITY TO PERFORM -

- TELEOPERATIONS/ROBOTICS
  - OTV COMPONENT CHANGEOUT
  - OTV HANDLING AND TRANSLATION
  - EVA CREW TRANSLATION

FIGURE 5-1
OTV MAINTENANCE AND SERVICING TECHNOLOGY DEVELOPMENT (CONTINUED)

DESCRIPTION OF TECHNOLOGY:

DEVELOP CAPABILITY TO PERFORM -

- EVA OPERATIONS
  - OTV COMPONENT CHANGEOUT
  - VISUAL INSPECTION

RATIONALE AND ANALYSIS:

- COST OF MAINTENANCE/SERVICING ACTIVITIES IN SPACE MUST BE MINIMIZED
  - IVA (TELEOPERATIONS) COST ~1/10 EVA COST
  - LIMITED PERSONNEL AT SPACE STATION
- STUDY INDICATES ROUTINE MAINTENANCE CAN BE PERFORMED WITH TELEOPERATIONS
- TELEOPERATONS/ROBOTICS IMPLEMENTATION REQUIRES EVALUATION AND PROOFING
- EVA CAPABILITIES WITH NEW SUIT REQUIRES EVALUATION

FIGURE 5-1
OTV MAINTENANCE AND SERVICING TECHNOLOGY DEVELOPMENT (CONTINUED)

TECHNOLOGY OPTIONS:

- TELEOPERATIONS/ROBOTICS
  - DEGREE OF AUTOMATION
  - LOCAL Vs REMOTE (EARTH) CONTROL
  - TOOLS

- EVA OPERATIONS
  - TRANSLATION AIDS Vs FREE FLYING WITH TETHER
  - POWER-ASSISTED TOOLS Vs COMPONENT LATCH SYSTEMS Vs CONVENTIONAL METHODS
  - INFORMATION SYSTEM - VARIOUS TYPES OF DATA DISPLAYS AND COMMUNICATIONS METHODS (INCLUDING HAL)

FIGURE 5-1

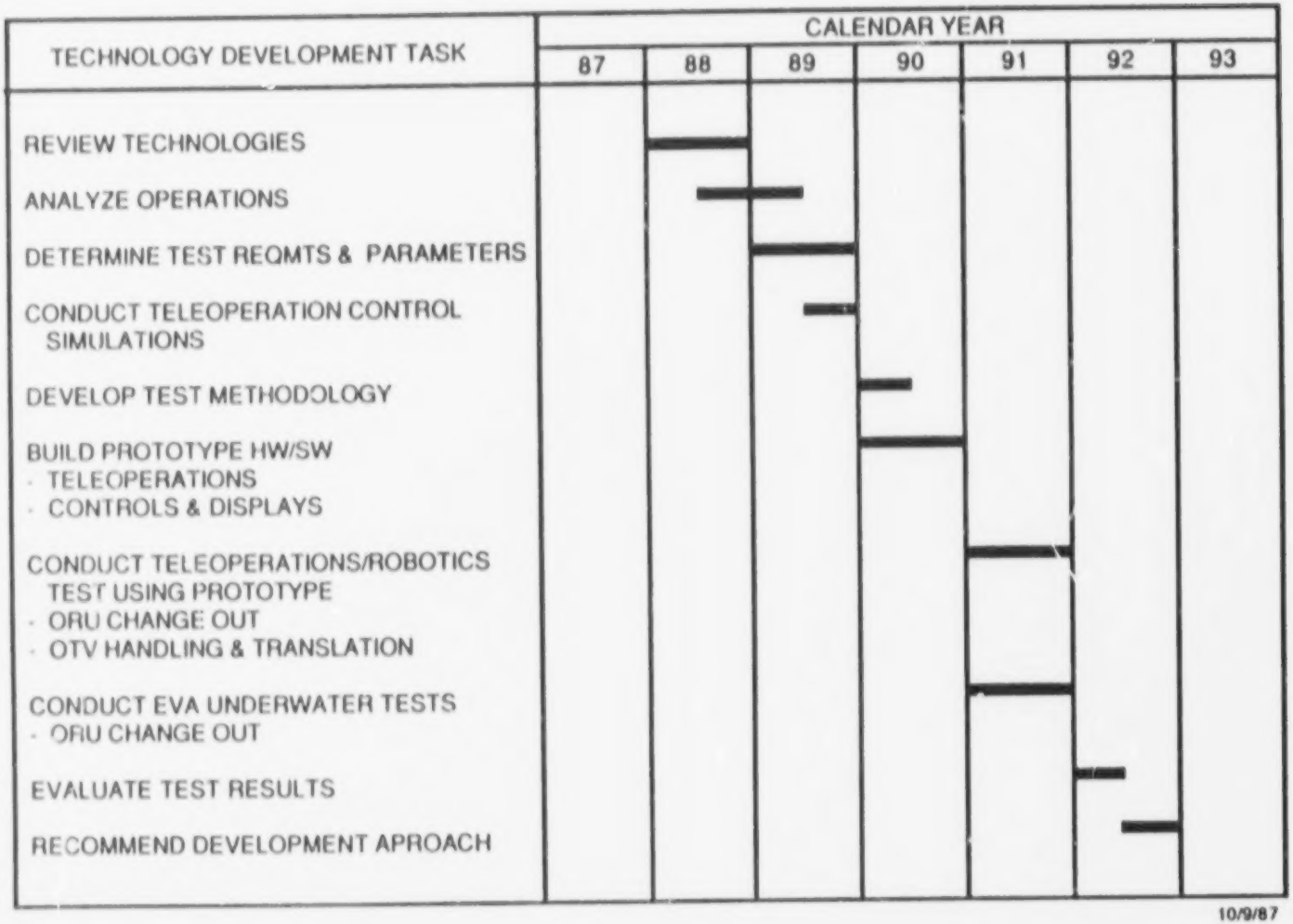
OTV MAINTENANCE AND SERVICING TECHNOLOGY DEVELOPMENT (CONTINUED)

TECHNICAL PROBLEMS:

- TELEOPERATIONS/ROBOTICS
  - POSITIONING ACCURACY AND REPEATABILITY
  - ARTICULATION/CONSTRAINTS
  - END-EFFECTOR AND TOOL CAPABILITY

- EVA OPERATIONS
  - DEXTERITY
  - OPERATIONAL TIME IN SPACE SUIT/FATIGUE
  - TIMELINES
  - NUMBER OF CREW INVOLVED

FIGURE 5-1A OTV MAINTENANCE & SERVICING TECHNOLOGY REQUIREMENTS SCHEDULE (GROUND TESTING)



10/9/87

5.1.2 OTV MAINTENANCE AND SERVICING OPERATONS - EVA

In the previously generated OTV Integrated Technology Development plan we addressed the development of the new space suit (8 psii) and the extravehicular maneuvering unit (EMU) needed to perform the OTV turnaround operations on orbit. For this plan we are assuming that this development will be taken care of by the Space Station Program. However, in order to perform the OTV maintenance and servicing tasks as a back-up to teleoperations, some technology related to EVA must be developed. Figure 5-2 is a summary of the ground development test requirements.

Table 5-1 shows the analysis and ground testing related to Heads-Up Display Audio Visual Logistics System (HAL). Table 5-2 covers EVA Power-Assisted Glvoe End Effector, and Table 5-3 covers the EVA Work Station. Table 5-4 covers the analysis, simulation, and ground testing for the EVA-OTV Maintenance and Servicing tasks.

EMU	Heads up display audio visual logistics system (HAL)	Monitor NASA HUD development program Integrate into EMU helmet Human factors (data assimilation, location) information channeling Data retrieval complexity	Operate in light & dark areas } IVA Data transfer 3 way } EVA Task complexity analysis On-orbit systems test Training test (conduct new tasks)
EMU	Power assisted glove end effector (PAGE)	Concept select & prototype manufacturing EMU integration 1-G demos vacuum tests (off gassing) NBF & KC-135 tests Productivity analysis	Glove removal replace test (IVA) EVA demo Hear transfer Task mock-up tests
EVA	Work station	Concept select & prototype manufacturing NBF tests Human factors (reach envelope, etc) OTV structural interface design	Design verification test Productivity test Set up take-down times Human factors compability
EVA	OTV tasks	Define EVA tasks Establish EVA task productivity Fabricate mock-ups Design verification via NBF tests Task procedures sequencing via NBF tests Ground to space-station job transfer	0 G EvA demos Translation of modules OTV repair replace subsystems Verify human factors design

21034220-1
268.340-14

Figure 5-2 EVA Operations Ground and Shuttle Sortie Development Test Requirements

Table 5-1. Heads-Up Display Audio Visual Logistic System (HAL)

DEFINITION OF TECHNOLOGY REQUIREMENT

1. TECHNOLOGY REQUIREMENT (TITLE): Heads-Up Display Audio Visual Logistic System (HAL)

2. TECHNOLOGY CATEGORY: EVA

3. OBJECTIVE ADVANCEMENT REQUIRED: Consolidate ground tasks for on-orbit conversion. Provide real-time sophisticated data to EVA crewmember.

4. CURRENT STATE OF ART: NASA/JSC has initiated a technology demonstration program

5. DESCRIPTION OF TECHNOLOGY:

Aircraft-style heads-up display system, voice recognition system, and expanded computer system integrated into the EMU.

6. RATIONALE AND ANALYSIS.

Real-time data assimilitation and/or transfer for complex OTV EVA tasks including OTV construction, maintenance, and repair as well as OTV payload transfer. In addition to streamlining EVA operations and saving time, the HAL system expands the complexity of EVA tasks and decreases ground-based EVA to crewmember training.

7. TECHNOLOGY OPTIONS:

Heads-up Display:

a. LED
b. LCD
c. VCR

Data transfer:

a. Fiber optics
b. Electrical

8. TECHNICAL PROBLEMS:

Integrated a heads-up display system into a pure O_2 environment.

Table 5-1 . Heads-Up Display Audio Visual Logistic System (HAL), Contd

1. TECHNOLOGY REQUIREMENT (TITLE): Heads-Up Display Audio Visual Logistic System (HAL)

9. POTENTIAL ALTERNATIVES: -

10. PLANNED PROGRAMS OR UNPERTURBED TECHNOLOGY ADVANCEMENT:

DARPA heads-up Display program.

11. RELATED TECHNOLOGY REQUIREMENTS

Development of voice synthesis/voice recognition system.

Advanced displays, data transmission.

Table 5-2. EVA Power-Assisted Glove End Effector

DEFINITION OF TECHNOLOGY REQUIREMENT

1. TECHNOLOGY REQUIREMENT (TITLE): EVA Power Assisted Glove End Effector

2. TECHNOLOGY CATEGORY: EVA

3. OBJECTIVE ADVANCEMENT REQUIRED: Reduce crewman fatigue, providing expanded work capability.

4. CURRENT STATE OF ART: NASA/JSC CR&D Program initiated 11/83.

5. DESCRIPTION OF TECHNOLOGY:

The power tool functions of reciprocating and rotary motion will be integrated as a streamlined tool into an EMU compatible glove.

6. RATIONALE AND ANALYSIS:

Repetitive tasks such as bolt/module removal/replace exerts a torque upon the EVA crewman's wrist and arm, inducing fatigue and limiting productivity. The use of a power tool will lessen the requirement of strict EVA task sequencing to reduce fatigue.

7. TECHNOLOGY OPTIONS:

Brushless dc motor reciprocating/rotary motion to be integrated:

a. Into EMU glove
b. Used as a separate tool

8. TECHNICAL PROBLEMS:*

*Operation in pure O_2 EMU environment

*Tool offgassing

*Power requirement

*Quick disconnect

Table 5-2. EVA Power-Assisted Glove End Effector

1. TECHNOLOGY REQUIREMENT (TITLE): EVA Power-Assisted Glove End Effector

9. POTENTIAL ALTERNATIVES: -

10. PLANNED PROGRAMS OR UNPERTURBED TECHNOLOGY ADVANCEMENT.
-

11. RELATED TECHNOLOGY REQUIREMENTS: -

Table 5-3. EVA Work Station

DEFINITION OF TECHNOLOGY REQUIREMENT

1. TECHNOLOGY REQUIREMENT (TITLE): EVA Work Station

2. TECHNOLOGY CATEGORY: EVA

3. OBJECTIVE ADVANCEMENT REQUIRED: Provide restraint and work station for crewman tasks on OTV maintenance

4. CURRENT STATE OF ART: NASA/JSC CR&D Program initiated 11/83.

5. DESCRIPTION OF TECHNOLOGY:

The EVA work station will provide required crewman restraint and work area for module replacement, subsystem repair, and OTV checkout. The system will be easily adjusted to provide the maximum work envelope with minimal setup/tear down time.

6. RATIONALE AND ANALYSIS:

The effective use of the EVA crewmember and the optimal productivity of each task is a direct function of the EVA work station and its maneuverability. The work station will be used as the prime EVA equipment demonstrator since most EVA sequences will be conducted from the work station.

7. TECHNOLOGY OPTIONS:

a. Adhesive bending work station (no scar to worksite)

b. Work platform on RMS-type structure

c. Integrates into EMU

8. TECHNICAL PROBLEMS:

Six degrees of freedom maneuverable without crewmember disengage.

9. POTENTIAL ALTERNATIVES: -

10. PLANNED PROGRAMS OR UNPERTURBED TECHNOLOGY ADVANCEMENT: -

11. RELATED TECHNOLOGY REQUIREMENTS: -

Table 5-4 . EVA OTV Maintenance/Servicing Tasks

DEFINITION OF TECHNOLOGY REQUIREMENT

1. TECHNOLOGY REQUIREMENT (TITLE): Page 1 of 3

EVA - OTV Maintenance/Servicing Tasks

2. TECHNOLOGY CATEGORY: EVA

3. OBJECTIVE ADVANCEMENT REQUIRED: Provide EVA operations capability to maintain/service an OTV at the Space Station using advanced space suit.

4. CURRENT STATE OF ART: EVA activity in Shuttle with present space suit.

5. DESCRIPTION OF TECHNOLOGY:

Develop capability to perform: 1) EVA maintenance/servicing tasks for a space-based OTV such as remove and replace avionic modules, advanced space engine, propellant tank modules, etc.; 2) inspection tasks for total OTV; 3) repair tasks for an aerobrake; and 4) contingency remove and replace operations for other components that would normally be maintained with automated means.

6. RATIONALE AND ANALYSIS:

Analysis in this study has indicated the type of maintenance/servicing tasks that would be required to be performed EVA by a crewman for routine maintenance, tasks that need to be evaluated compared to using automated equipment, and tasks that would be required for contingency operations as backup to automated tasks. The capability to perform these tasks and the evaluation of EVA tasks versus automated tasks needs to be undertaken.

7. TECHNOLOGY OPTIONS:

a. Mobility aids versus free flying with tether

b. Power-assisted tools including glove end effector

c. Various module attachment/interface arrangement

d. Different types of data displays including HAL

e. EVA operations versus automated operations

Table 5-4. EVA OTV Maintenance/Servicing Tasks, Contd

1. TECHNOLOGY REQUIREMENT (TITLE): EVA Maintenance Servicing Tasks — Page 2 of 3

8. TECHNICAL PROBLEMS:

- o Dexterity
- o Operational time in the space suit/fatigue
- o Timelines
- o Number of crewmen involved

9. POTENTIAL ALTERNATIVES:

Highly sophisticated automated operations

10. PLANNED PROGRAMS OR UNPERTURBED TECHNOLOGY ADVANCEMENT: -

11. RELATED TECHNOLOGY RQUIREMENTS:

- o Advanced Space Suit
- o HAL
- o Power-assisted glove end effector

5.2 OTV MAINTENANCE AND SERVICING OPERATIONS AND SUPPORT EQUIPMENT

Two shuttle sortie missions are planned in this area. The first will evaluate the maintenance and servicing operations using teleoperations and the support equipment technology and the second the EVA operations.

5.2.1 MAINTENANCE FACILITIES/EQUIPMENT SHUTTLE SORTIE MISSION

Initial testing of the maintenance facility and equipment components in space will occur on a Shuttle sortie mission. This will ensure equipment operation during the applied concept evaluation of the maintenance technology development mission at the Space Station (TDM). The proposed sortie mission is presented in Figure 5-AA.

The schedule for the start of the analysis for this task is shown along with the time of the proposed sortie flight. The funding required from the initiation of the analysis task through ground testing, and including the sortie mission hardware is shown. The cost of the Shuttle flight is not included. The derivation of the funding can be found in Section 8.0.

5.2.2 SHUTTLE SORTIE MISSION

The advanced space suit, associated equipment, and planned operational tasks are proposed to be evaluated during Shuttle sortie tests (Figure 5-3). EVA operations are essential to OTV servicing operations as a back-up to teleoperations. The EVA system is being refined and developed to enhance the efficiency of man working in the space environment. The schedule for the start of the analysis for this task is shown along with the year of the proposed two sortie flights. The funding required from the initiation of the analysis task through ground testing, and including the sortie mission hardware is shown. We have only included the funding required for the EVA work station and operations tasks. The cost of developing the advanced space suit should be charged to the Space Station. The cost of the flight is not included. Derivation of the funding can be found in Section ?.

Figure 5-AA MAINTENANCE FACILITY/SUPPORT EQUIPMENT - SORTIE TESTS

OBJECTIVE:

Zero-g verification of the capability to use an automated arm to remove and replace simulated OTV components and evaluation of OTV translation and berthing rotation equipment, including large component translating and handling equipment.

JUSTIFICATION:

Equipment control algorithms and hardware need precursor verification in the space environment.

DESCRIPTION:

Conduct simulated OTV, maintenance dock and equipment evaluation operations to prove the concepts. The shuttle would provide the command control, monitor and instrumentation equipment for compatibility assessment of the following items:

- Remote control arm (automatic & man-in-the loop operation)
- Scissor crane for engine removal
- Crewmen translation equipment
- OTV translating & berthing rotation equipment

For costing purposes the following equipment was assumed to be required for the sortie mission.

ITEM	WEIGHT (lb)
Controls and displays	80
Motorized carriage components	210
Berthing and support system components	250
Remote control arm/scissor crane components	450
Support truss	250

Figure 5-3 EVA OPERATIONS - SORTIE TESTS

OBJECTIVE:

Zero-g verification of the ability of the astronauts to use the advanced space suit/EMU and evaluation of equipment capabilities to meet the requirements. In addition, verify the capability of the astronauts in the space suit to effectively use the EVA work station and perform simulated OTV maintenance tasks.

JUSTIFICATION:

The space suit, life support systems and associated equipment must be tested in the actual space environment before full commitment to the space station EVA operations.

DESCRIPTION:

The astronauts will perform EVA operations in the shuttle cargo bay. They will evaluate the advanced space suit which will have the following technology development features:

- Zero prebreathe capability & EMU
- Heads-up display
- Power-assisted glove

The astronauts will perform representative maintenance operations within an EVA workstation to provide system & human factors, design feedback and EVA procedures calibration.

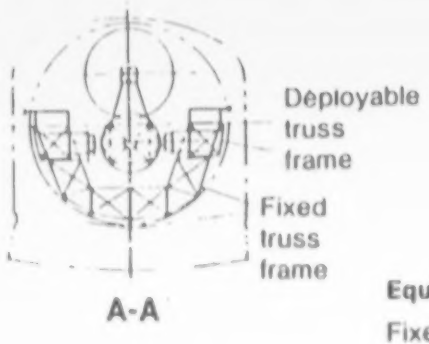
For costing purposes, the following equipment was assumed to be required for the sortie mission:

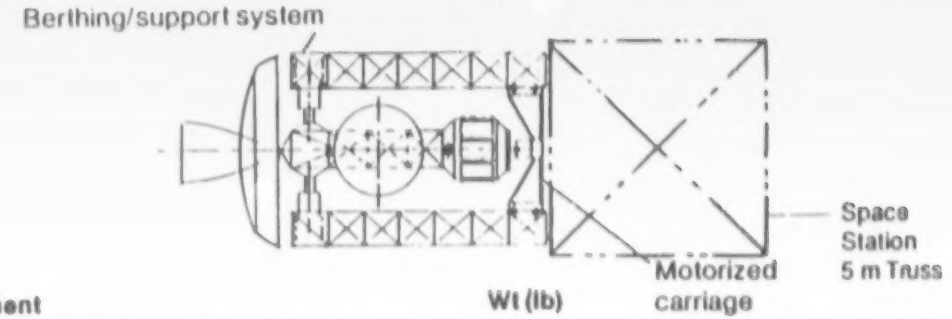
ITEM	WEIGHT
Space Suit/EMU	GFE
EVA Work Station	150
Simulated Adapters, Interface Equipment Mockups, Tools, etc. • Engine • Avionics • ACS	250

5.3 OTV MAINTENANCE/SERVICING OPERATIONS AND SUPPORT EQUIPMENT TECHNOLOGY DEVELOPMENT MISSION

The OTV maintenance/servicing operations and support equipment TDB (see Figure 5-4) consists of two open truss frames, a motorized carriage, a berthing/support system, a simulated OTV, and cherry picker type devices for restraining the astronauts. The OTV is attached to the carriage and berthing system and the entire package (frames, OTV, carriage, berthing system, etc.) is deployed from the Shuttle and attached to a space station truss. The TDM is supported in the Shuttle with an open truss to perform maintenance verification tasks, docking and berthing, and payload mating tasks.

FIGURE 5-4 OTV MAINTENANCE, SERVICING & DOCKING TDM





Equipment	Wt (lb)
Fixed truss frame (stays with Shuttle)	780
Deployable truss frames	600
EVA manipulator	400
Motorized carriage	415
Berthing/support system	500
Simulated OTV	1,290
Truss frames berthing systems	380
Electrical & instrumentation	180
Support latches for deployable truss frame	85
Total	4,630

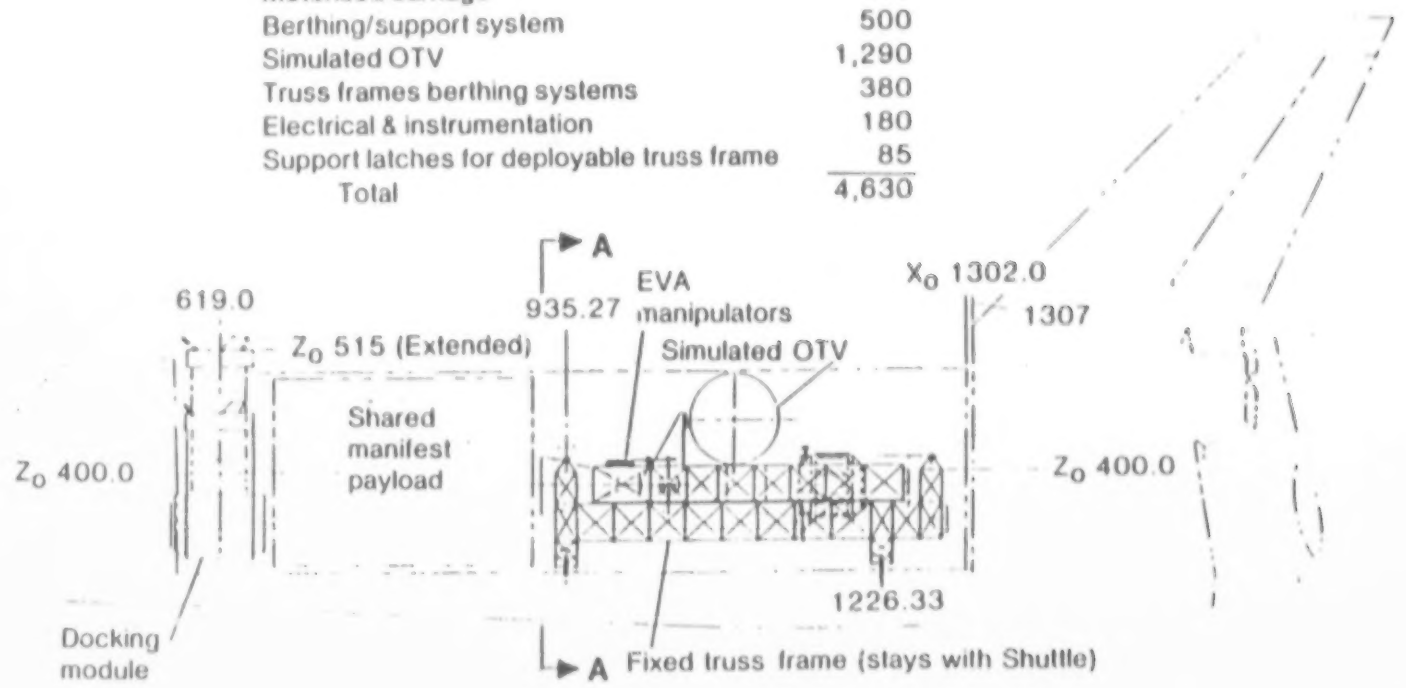


Figure 5-5 describes the components of the simulated OTV used for the maintenance TDM.

The modules shown can be removed from the simulated OTV for the maintenance TDM. The berthing interface is at the forward of the core module.

The module sizes were selected to be representative of actual sizes for an OTV in order to develop the capability to handle this type of equipment in space.

Equipment such as avionics packages and ACS modules can be replaced automatically using the RMS located on a space station truss. A typical changeout is shown in Figure 5-6 for an ACS module. The changeout starts by attaching the RMS to a fitting on the ACS module and the module is then disconnected from the OTV. The ACS module is next transported by the RMS to a holding fixture located on a space station truss and attached to the fixture. The changeout is completed by reattaching the RMS to the ACS module and reversing the procedures. The same procedures apply to avionics equipment changeouts. The avionics modules will also be changed out by EVA to evaluate this capability versus automated.

This chart also shows the cherry picker equipment necessary for EVA crew member translation to and from the work site. The cherry picker has personnel restraints and is mounted on a rail carriage system that allows the required mobility and OTV access for maintenance EVA operations.

The carriage also has the ability to rotate the OTV about its axis for easier servicability by an EVA astronaut or RMS.

FIGURE 5-5 SIMULATED OTV

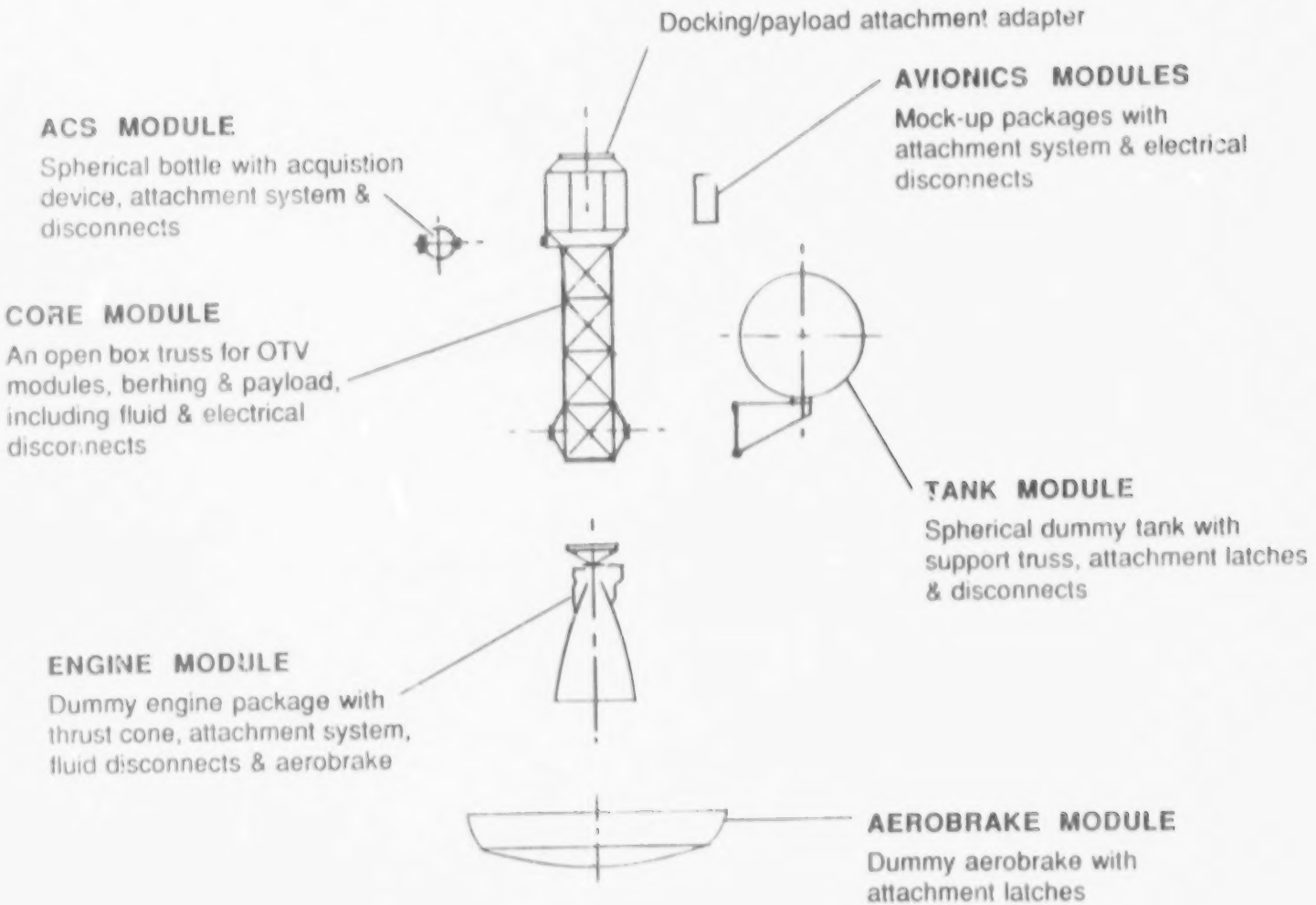
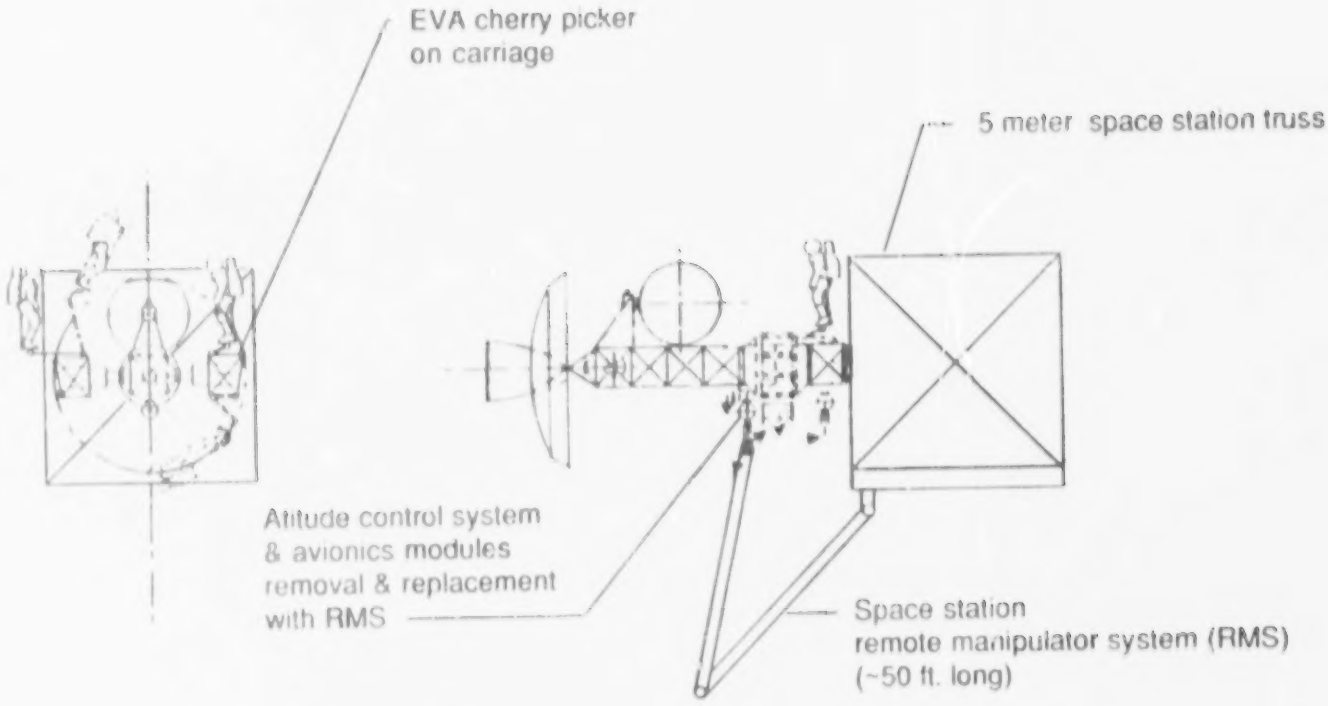

Docking/payload attachment adapter
AVIONICS MODULES
Mock-up packages with attachment system & electrical disconnects
ACS MODULE
Spherical bottle with acquistion device, attachment system & disconnects
CORE MODULE
An open box truss for OTV modules, berhing & payload, including fluid & electrical disconnects
TANK MODULE
Spherical dummy tank with support truss, attachment latches & disconnects
ENGINE MODULE
Dummy engine package with thrust cone, attachment system, fluid disconnects & aerobrake
AEROBRAKE MODULE
Dummy aerobrake with attachment latches

FIGURE 5-6

BASIC OTV MAINTENANCE FACILITY & SUPPORT EQUIPMENT



Not shown

- TV cameras
- Lighting
- Propellant leak detection sensors
- RMS adapters
- EVA hand tools
- Command center accommodations

The actual maintenance TDM involves Level I maintenance activities (at the OTV dock). It was not under the scope of this contract to look at Level II modules removed and brought into a pressurized area in the station.

The simulated OTV components that were identified for maintenance concept proofing at the Space Station are listed in Table 5-M. The avionic modules will be removed and replaced by both EVA and IVA/RMS operations and the ACS modules are replaced via IVA/RMS. All other OTV maintenance activities will involve EVA operations. One damage repair operation to be accomplished on the aerobrake while on the vehicle has been injected into the maintenance scenario, but the other maintenance activities all involve remove and replace action. The IVA remove and replace operations will be accomplished with crew control of an RMS or the RMS may be programmed to do the task entirely under computer control. Visual inspection techniques will be performed and evaluated in conjunction with the other individual maintenance operations.

The proposed ground and Shuttle sortie EMU/EVA operations tests are precursors for a part of the maintenance TDM. Other areas are also covered by the TDM and these are discussed in the following sections. The TDM will use some of the ground and sortie test equipment such as EVA work station and tools.

Table 5-M. Subsystems Selected for Maintenance Tests

o Avionic modules	-	Several representative RF and computer modules for EVA remove and replace and IVA/RMS remove and replace
o Core section	-	Fuel cell and battery EVA remove and replace
	-	ACS IVA/RMS remove and replace
o Engine module	-	EVA remove and replace
o Tank module	-	EVA remove and replace
o Aerobrake	-	EVA repair

NOTE: Visual inspection to be a distributed function on all tasks.

SECTION 6.0
DOCKING AND BERTHING

This section covers the areas of docking and berthing. The requirements for the ground and Shuttle sortie tests are summarized. The TDM for the initial station is referenced.

6.1 DOCKING AND BERTHING ANALYSIS AND GROUND TESTING

The requirements identified for the docking and berthing development ground tests are presented in Figure 6-1. We have listed the development tasks and the recommended methods of accomplishment, along with specific functions to be developed, proofed, and verified.

6.2 DOCKING AND BERTHING SHUTTLE SORTIE MISSION

The requirements identified for the docking and berthing development Shuttle Sortie tests are presented in Figure 6-1. The figure shows what needs to be accomplished in orbit as opposed to on the ground.

A docking and berthing system feasibility mission (Figure 6-2) is proposed to be accomplished on the Shuttle orbiter to ensure design capabilities are adequate to support the intended use. This approach will provide a proof of concept system for the docking and berthing TDM on the Space Station. The schedule for the start of the analysis for this task is shown along with the time of the proposed sortie flight. The funding required from the initiation of the analysis task through ground testing, and including the sortie mission hardware is shown. The cost of the Shuttle flight is not included. Derivation of the funding can be found in Section 6.0

Development technology task	Ground tests	Shuttle sortie
Data systems	OMV computer capacity for use attached to OTV. Memory, & software	Evaluate performance of OMV computer & software Demonstrate performance
Ranging	Laser information processing, power levels, beam dispersion, accuracy & repeatability. Establish closing accuracies & alignment Fiducial marking location, size, color & pattern	Demonstrate performance of laser ranging in space environment both automatically & manually Verify illumination & discernment design in manual mode
Stability & control	Gain & transfer function for OTV/OMV combination Establishment of closure rate, angle & rotational accuracies	Orbital verification of control. Minimization of impact loads
Automatic monitor & control with manual override	Displays for timely indication of closing rates: • Control rates, distances & attitudes • Anticipation displays, warning & safety functions	Establish useable boundaries for maneuvering rates & distances. Minimize EMI/EMP
System performance & instrumentation	Develop sensors & data handling for • Fuel Flows • Rates • Distances • Accelerations • Attitudes • Power system • Engine performing • Loads • Residuals • Computer functions	Demonstrate instrumentation system performance in orbit Verify interface to TDRSS
Assembly of OTV/ OMV system	Structure fits. Simulated & functional interface fits Software compatibility. Develop system integration technique	Demonstration in orbit functionality of system
Attach points	Develop attach points for RMS, docking & berthing positions	Evaluate adequacy of shuttle attach points for launch, RMS & sortie deployments
Extraction of OTV from shuttle using the RMS	Generate procedures for manipulating the OTV from the cargo bay with the RMS	Validate procedures for deploying OTV from shuttle during sortie
Detach RMS from OTV	Procedures for non-load detachment	In-orbit evaluation of OTV release or hand-off
Securing at docked position	Assessment of shock loads, clamping functions, release biases, power requirements, command & control	Assessment of securing & release of OTV from docked position in orbit
Securing at berthed position	Development of coupling devices, umbilicals, hold-down mechanisms & refurbishment procedures	In-orbit demonstration of berthing requirements

21034220-8
288.340-9

Figure 6-1 Docking and Berthing Development Test Requirements

For costing purposes the following equipment was assumed to be required for the sortie mission.

ITEM	WEIGHT (lb)
Truss frames and Berthing system	190
Simulated OTV frame, berthing latches	300
Avionics and instrumentation	90
Fixed truss frame - Shuttle support	200
Shuttle RMS	GFE
OMV	GFE

Objective:

To provide zero-g verification of the capability of the OMV/simulated OTV with assistance from the RMS to dock with a docking mechanism during berthing operations on the shuttle

Justification:

Verification of equipment hardware, software & techniques in the form of a sortie test is necessary to allow system deployment to the space station. This will provide initial evaluation of the system & a degree of safety for extended proofing operations from the space station

Description:

Perform rendezvous, docking & berthing operations using an OMV, simulated OTV, shuttle RMS & docking arm. The OTV/OMV will be deployed & berthed with the RMS. The vehicle will dock with an arm extending from the shuttle. The arm will contain the appropriate targets & docking interface. The shuttle will also provide the necessary command control, monitor & instrumentation to allow adequate in-space evaluation of the system

Figure 6-2 Docking and Berthing Sortie Tests

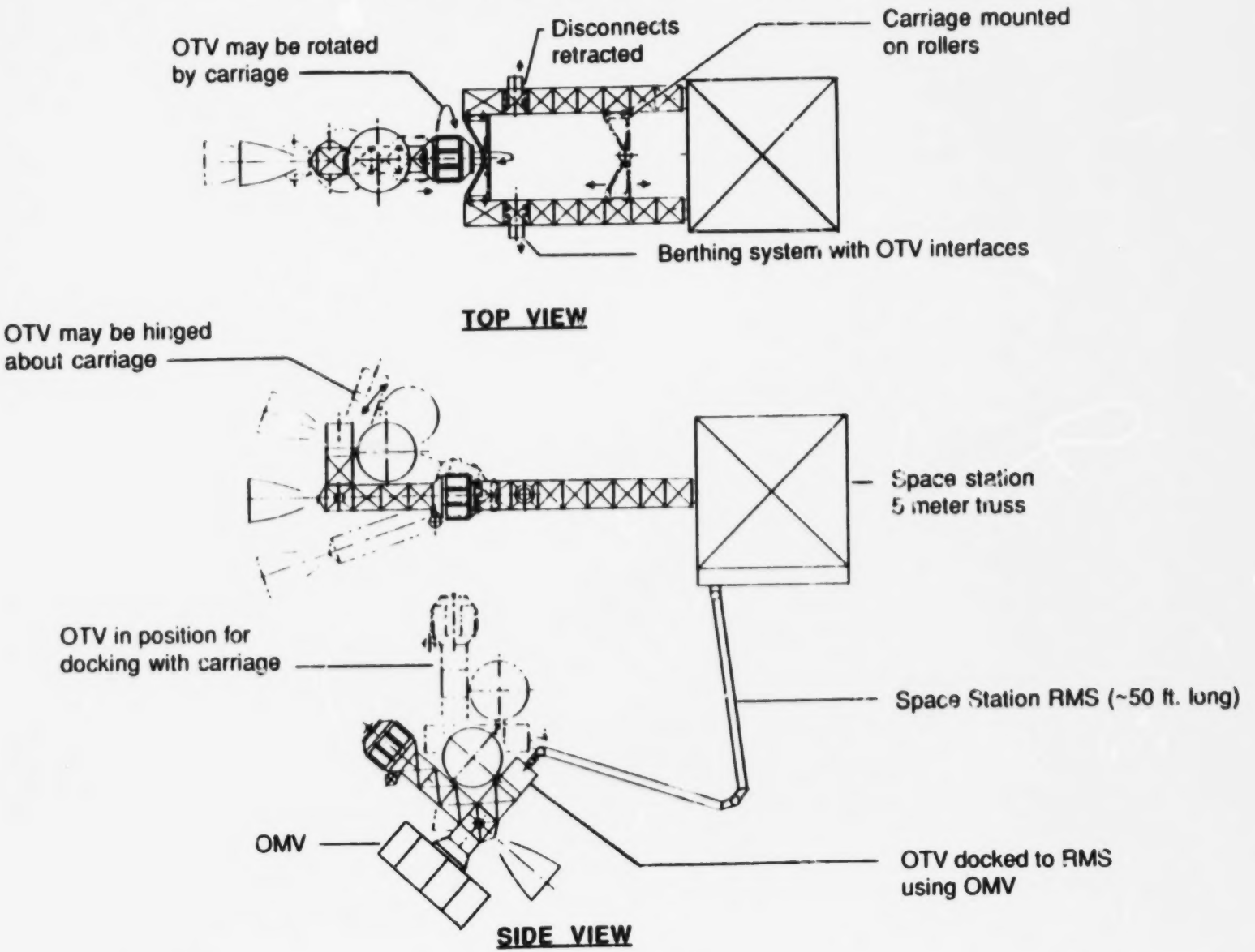
6.3 DOCKING AND BERTHING TECHNOLOGY DEVELOPMENT MISSION

The docking and berthing TDM uses the test equipment included in the maintenane/servicing TDM, mainly the simulaed OTV and the docking carriage.

Depending on the docking capabilities required by the operational OTV, the docking method shown on Figure 6-3 may be the selected approach. If this is the case, an OMV is used to bring the OTV into the station for docking and berthing. The OMV can be used to position the OTV so that it can be picked up by the RMS as shown on the chart. The RMS is then used to dock the OTV to the carriage. Using the carriage, the berthing operation would be performed by moving the simulated OTV with the carriage to the right and engaging the berthing system and checking the interfaces.

The proposed docking and berthing ground and shuttle tests are precursors to the activities on this TDM. The TDM will use some of the ground and sortie test equipment such as docking and berthing latches.

FIGURE 6-3 DOCKING OPERATION


OTV may be rotated by carriage
Disconnects retracted
Carriage mounted on rollers
Berthing system with OTV interfaces
TOP VIEW
OTV may be hinged about carriage
Space station 5 meter truss
OTV in position for docking with carriage
Space Station RMS (~50 ft. long)
OMV
OTV docked to RMS using OMV
SIDE VIEW

SECTION 7.0
OTV/PAYLOAD MATING/INTERFACE

This section describes the requirements and recommended ground and Shuttle sortie tests. A proposed sortie mission is described along with the estimaed costs for the tests. A summary of the TDM for the initial station is also included.

7.1 OTV/PAYLOAD/MATING INTERFACE DEVELOPMENT TESTS REQUIREMENTS

The requirement to develop a new type interface for the OTV and payload, to enable efficient mating operations at the Space Station, has been established. Current methods for attaching a payload to a vehicle commonly involves an adapter with extensive bolting arrangements at both ends of the interface. The interface is usually severed/separated by means of pyrotechnic devices installed on the center perimeter of the adapter and the payload is deployed with multiple spring-loaded actuators. This method offers an adequate payload interface for expendable missions. It provides for high structural loading at the interface and a simple reliable means for deployment of the payload, without adding much to the space debris. However, this type of interface, currently in use, does not accommodate remating of a reusable vehicle with a payload during turnaround operations in space. The reloading of the spring actuators, alignment, and attachment of the interfaces would require special support equipment and labor intensive EVA operations to accomplish the task.

A standard self-aligning, quick-disconnect OTV/payload interface needs to be developed, one that would eliminate the need for EVA and special support equipment during payload mating process. The new interface would accommodate RMS positioning and alignment of the payload on the OTV. The hold-down system could be implemented by incorporating latch-type mechanisms into the vehicle that would be controlled through the vehicle command system.

Table 7-1 summarizes the tests required on the ground and on a Shuttle sortie mission.

7.2 OTV/PAYLOAD MATING/INTERFACE SHUTTLE SORTIE MISSION

Figure 7-1 briefly describes the proposed Shuttle sortie tests identified for proving-out elements of the new type interface in the space environment. During the tests, the operations and equipment components will be assessed for adequacy and compatibility. The schedule for the start of the analysis for this task is shown along with the time of the proposed sortie flight. The funding required from the initiation of the analysis task, through ground testing, and including the sortie mission hardware is shown. The cost of the Shuttle flight is not included. Derivation of the funding can be found in Section 8.0.

For costing purposes, the following equipment was assumed to be required for the sortie mission:

ITEM	WEIGHT (lb)
Simulated OTV and payload with adapter and quick-disconnects	200
Shuttle RMS	GFE

Table 7-1 . OTV Payload Integration Operations Development Test Matrix

OTV Payload Operations	Development Tests: Ground	Development Tests: Shuttle Sortie	Objective of Test Program	Rationale for Test Location
Handling	x	x	Test the concepts of payload transfer from Space Station berthing to OTV interface	Ground tests to establish procedures. Sortie tests required to confirm procedures in actual working environment
Mating	x	x	Develop the procedures required for mating payloads on an OTV for attachment ease and interface verification	Ground tests to establish procedure and interface design. Sortie tests required to verify attachment interface
Checkout	x		Validate the methods of payload checkout after mating & before launch of OTV	Sortie tests not required. Checkout from Space Station is the same as on ground simulator
R&R payload components	x		Test concepts of servicing payloads attached to an OTV when berthed at Space Station	Ground tests to establish RU replacement methods. Sortie tests not required, covered by EVA operation, Sortie tests
Demating	x	x	Test the concept of payload removal from OTV due to failure detection	Ground tests to establish procedures. Sortie tests required to confirm procedures in actual working environment

Objective:

Zero-g verification of the capability to mechanically mate a payload and OTV which have standard quick disconnect interfaces

Justification:

The interfaces, operational methods and equipment need to be tested in the actual operating environment to assure adequacy and compatibility under zero-g conditions

Description:

The payload will be translated and positioned on the simulated OTV interface with the shuttle RMS. The interface will be latched and verified from equipment placed in the shuttle cabin. The shuttle will also provide monitor and instrumentation equipment

Figure 7-1 Payload Mating/Interface - Sortie Tests

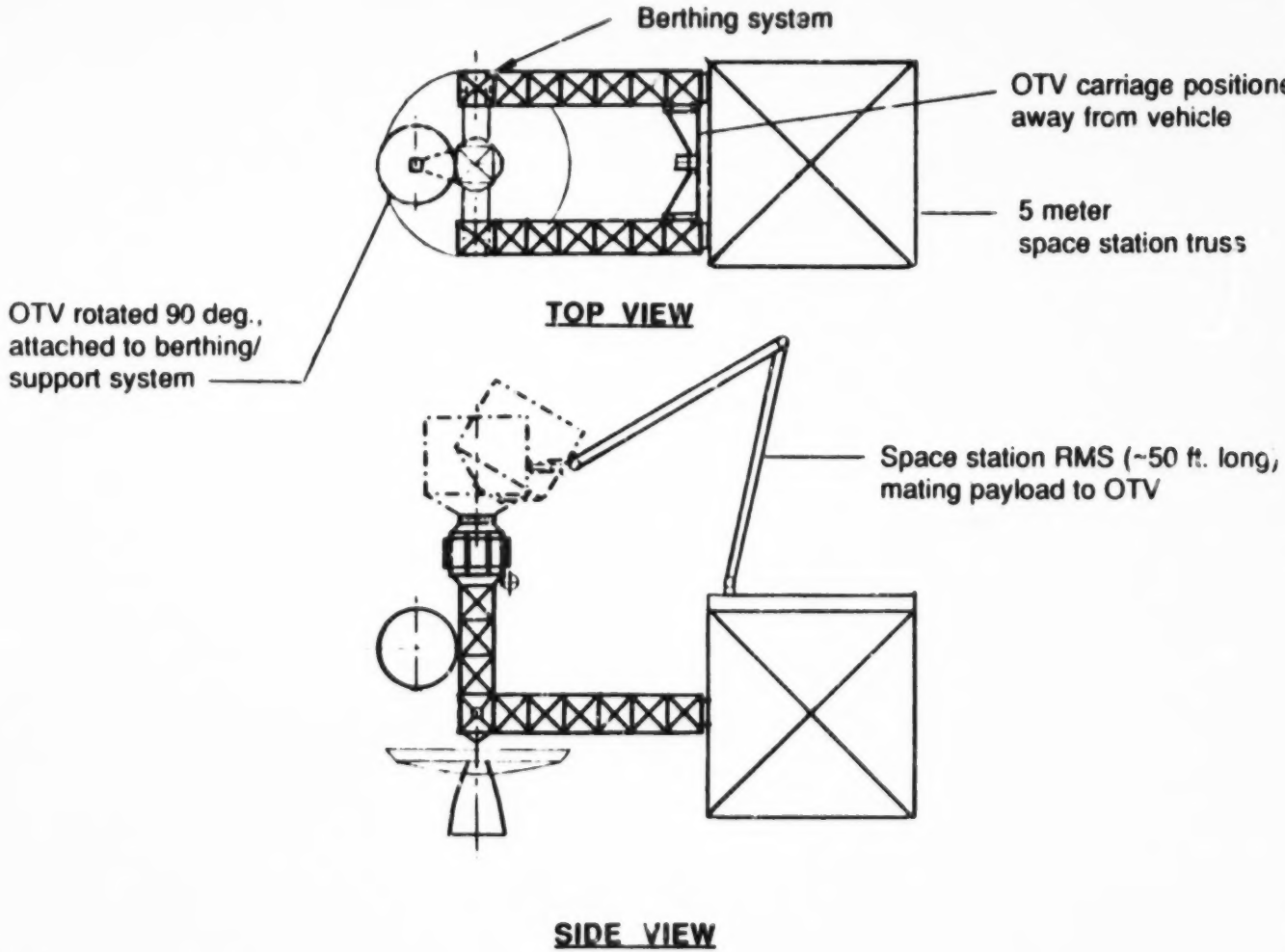
7.3 OTV/PAYLOAD MATING/INTERFACE TDM

The payload integration TDM will use the same equipment as the maintenance/servicing TDM. This TDM assumes that a simulaed payload would be available at the space station and that no additional equipment is needed to be launched.

To accomplish payload mating the OTV is rotated about the berthing system axis. The simulated payload is then transported from a fixture on the space station to the OTV using the space station RMS. Once mated to the OTV, checkout of the integration is performed. (SEE FIGURE 7-2)

The RMS is detached from the payload and returned to the station where a manned cherry picker device is attached to it. Two crewmen are then carried to the payload and perform a simulated remove and replace operation. After the EVA operation on the payload, the crewmen are returned to the space station. Then the payload is demated from the OTV and returned to the support fixture on the station.

FIGURE 7-2 CONCEPT FOR OTV/PAYLOAD INTEGRATION


Berthing system
OTV carriage positioned away from vehicle
5 meter space station truss
TOP VIEW
OTV rotated 90 deg., attached to berthing/ support system
Space station RMS (~50 ft. long) mating payload to OTV
SIDE VIEW

SECTION 8
TECHNOLOGY DEVELOPMENT TESTS COST ANALYSIS

This section delineates the costing analysis performed for the development tests described in the previous sections.

The following are the ground rules and assumptions used in this analysis:

- o All cost are ROM for planning purposes only
- o Costs are in constant FY 1987 M$
- o No fee, management resume or contingency are included
- o The Propellant Transfer Storage and Reliquefaction technology estimate are based on the Large Tank Cryogenic Storage Facility Study (NAS8-)
- o All other technologies are based on very preliminary and brief definition
- o No government support or STS costs are included
- o No flight on Sortie operations costs are included
- o ELV vehicle costs are included with appropriate technologies

8.1 AUTOMATED FAULT DETECTION/ISOLATION AND SYSTEM CHECKOUT

The funding required for the ground testing (see Section 3.0) for this technology is shown in Table 8-1.

8.2 CRYOGENIC PROPELLANT TRANSFER, STORAGE, AND RELIQUEFACTION

The funding required for the technology development in this area is shown in Section 4.4. This covers the ground testing, alternative ELV experiments, full scale (LH2 only) ground testing, Space Station TDM, and the development of the operational propellant storage tanks on the Space Station.

8.3 OTV MAINTENANCE/SERVICING/SUPPORT EQUIPMENT

Table 8-2 and 8-3 show the funding requirements for the ground testing and Shuttle Sortie Missions described in Section 5.1 and 5.2.

Table 8-4 shows the funding requirements for the TDM at the Space Station as described in Section 5.3. It also includes the following for the docking and berthing and OTV/Payload Mating/ Interface testing part of this TDM as described in Section 6.3 and 7.3.

TABLE 8-1. AUTOMATED FAULT DETECTION/ISOLATION AND SYSTEM CHECKOUT FUNDING REQUIREMENTS

Cost (87M$)	NR	-
	R	-
	OPS	-
	TOTAL	$10.0

FY 88 -	.2	
FY 89 -	1.0	SIMULATION
FY 90 -	1.0	
FY 91 -	3.0	HARDWARD
FY 92 -	4.0	
FY 93 -	.5	TEST
FY 94 -	.3	
	10.0	

TABLE 8-2. MAINTENANCE AND SERVICING GROUND AND SORTIE MISSION FUNDING REQUIREMENTS

Maintenance Facilities and Equipment

Cost (87M$)	NR	12.7
	R	2.5
	OPS	-
	TOTAL	15.2

FY 88 - .5	ANALYSIS
FY 89 - 1.0	
FY 90 - 6.0	HARDWARE
FY 91 - 5.7	
FY 92 - 2.0	SHUTTLE SORTIE
15.2	

TABLE 8-3. EVA OPERATIONS GROUND AND SORTIE MISSION FUNDING REQUIREMENTS

Cost (87M$)	NR	8.5
	R	2.2
	OPS	-
	TOTAL	10.7

FY 88 - .5	ANALYSIS
FY 89 - 4.2	HARDWARE
FY 90 - 4.0	
FY 91 - 2.0	SHUTTLE SORTIE

TABLE 8-4. MAINTENANCE/SERVICING/SUPPORT EQUIPMENT TECHNOLOGY DEVELOPMENT MISSION (TDM) FUNDING REQUIREMENTS

Cost (87M$)	NR	36.4
	R	12.1
	OPS	-
	TOTAL	48.5

FY 91	2.0
FY 92	12.0
FY 93	15.5
FY 94	14.0
FY 95	5.0
	48.5

8.4 DOCKING AND BERTHING

The funding required for the ground and sortie mission tests for this technology is shown in Table 8-5.

8.5 OTV/PAYLOAD MATING/INTERFACE

Table 8-6 shows the funding required for the ground and sortie mission tests for this technology.

8.6 INTEGRATED TECHNOLOGY DEVELOPMENT PLAN FUNDING

Table 8-7 summarizes the different funding areas for the Integrated Technology Development Plan. The three cyrogenic propellant development options are shown in Section 4.4.

TABLE 8-5. DOCKING & BERTHING GROUND AND SORTIE MISSION FUNDING REQUIREMENTS

		GND	SORTIE	COMBINED
Cost (87$)	NR	7.0	8.4	15.4
	R	-	2.5	2.5
	OPS	-	-	
	TOTAL			17.9

FY 88	1.5	ANALYSIS
FY 89	2.0	SIMULATION
FY 90	6.9	HARDWARE
FY 91	6.0	SHUTTLE SORTIE
FY 92	2.0	
	17.9	

TABLE 8-6. OTV/PAYLOAD MATING/INTERFACE GROUND AND SORTIE MISSION FUNDING REQUIREMENTS

		GND	SORTIE	COMBINED
Cost (87M$)	NR	2.3	4.1	6.4
	R	-	.9	.9
	OPS	-	-	-
	TOTAL			7.3

FY 88 - .5	ANALYSIS
FY 89 - 2.0	SIMULATION
FY 90 - 2.0	HARDWARE
FY 91 - 1.8	
FY 92 - 1.0	SHUTTLE SORTIE

TABLE 8-7. TECHNOLOGY DEVELOPMENT PLAN FUNDING*

AREA \ FY	88	89	90	91	92	93	94	95	96	97	TOTAL $M
• AUTOMATED FAULT DETECTION/ISOLATION AND SYSTEM CHECKOUT (GR)	.2	1.0	1.0	3.0	4.0	.5	.3				10.0
• CRYOGENIC PROPELLANT TRANSFER	SEE PROPELLANT DEVELOPMENT OPTIONS COST CHART										
• MAINTENANCE FACILITIES/ AND EQUIPMENT (GR & SORTIE)	.5	1.0	6.0	5.7	2.0						15.2
• EVA OPERATIONS (GR & SORTIE)	.5	4.2	4.0	2.0							10.7
• MAINTENANCE/SERVICING OPERATIONS & SUPPORT EQUIPMENT (TDM)				2.0	12.0	15.5	14.0	5.0			48.5
• DOCKING & BERTHING (GR & SORTIE)	1.0	2.0	6.9	6.0	2.0						17.9
• OTV P/L MATING (GR & SORTIE)	.5	2.0	2.0	1.8	1.0						7.3

*DOESN'T INCLUDE LAUNCH OR OPERATIONS COSTS

Table 8-8 summarizes the total funding requirements for the OTV accommodations at the Space Station. The total includes the technology development (cryogenic Option #2 shown for reference) and the development of the operational accommodations. The later data is presented in Vol II Section 7.2.